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AN

INTRODUCTION

TO

NATURAL PHILOSOPHY:

DESIGNED AS A

TEXT BOOK,

FOR

THE USE OF THE STUDENTS IN

YALE COLLEGE.

IN TWO VOLUMES.

VOL. II.—PNEUMATICS, ELECTRICITY, MAGNETISM, AND OPTICS.

COMPILED FROM VARIOUS AUTHORITIES.

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ADVERTISEMENT.

THE original design of the compiler of this work, was merely to reduce Bridge's Mechanics to such a form and size, as would be adapted to the limited time and opportunities of a class in college. With this view the following changes were made.

1. By printing in a smaller type and more compactly, and retaining such parts only as were deemed most important to the general scholar, the six hundred pages of which the original work consisted, were reduced to one hundred and eighty eight.

2. The most important propositions were more distinctly enunciated, and separated from the context. In order still farther to give them peculiar prominence to the eye of the student, they were marked by the word *Theorem*.

3. New definitions were supplied, explanatory notes added or interspersed, and occasional extracts from other writers introduced.

4. A number of new problems were added, or substituted; and, in some instances, such as were expressed in the general terms of A, B, &c., were so modified as to be more interesting and practically useful to the young learner.

The impossibility, however, of finding corresponding treatises on the other branches of Natural Philosophy, and the general dissatisfaction which prevailed with Enfield's Institutes, (the work then used as a Text Book,) were urged upon the writer as reasons for completing a full course of the Elements of Natural Philosophy,—a task which he has attempted to fulfil in the work now offered to the public. Although a *compilation*, merely, according to the terms of agreement with the publisher, was all that the writer felt himself bound to execute, yet the work has approached nearer and nearer to an original composition as it has advanced. Indeed, the greater part of the second volume has been composed anew.

In most of our colleges, within a few years, so many new departments of study have been introduced, that the want of time for the completion of a full and thorough course of scientific studies, is seriously felt. The necessity of making this work extremely concise,

compared with the great extent of the subjects of which it treats, has been repeatedly suggested to the compiler by his brethren of other colleges, and has been as strongly felt in reference to his own pupils. Although, therefore, it were highly desirable that works designed for our colleges, should be something more than "Introductions," "Abridgments," and "Elements," yet since, in the present work, an *Introduction* is all that we can fairly presume to have given, so it is all that we feel disposed to claim; expressing, however, the belief, that it offers some advantages over the similar works heretofore used in our colleges, and adding the hope that the continued advancement of science in our country, may justify a corresponding improvement in our text books, and the lectures founded upon them.

As the two volumes have three hundred and eleven wood cuts, beside a copper plate engraving of the steam engine, the price at which it is afforded by the publisher is necessarily enhanced by these additions; but they doubtless will be found to add greatly to the convenience and value of the work, especially for Institutions which have not yet supplied themselves with a full assortment of philosophical apparatus. Indeed, when apparatus is actually exhibited to the learner, he usually acquires a much better knowledge of it, if he has previously studied its principles as illustrated by diagrams.

Yale College, August 15, 1832.

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OF PNEUMATICS.

522. Pneumatics *is that branch of Mechanics, which treats of the equilibrium and motion of elastic fluids.*

Those laws of equilibrium which are founded on the peculiar nature of fluids, arising from the mobility of their particles, are equally applicable to Hydrostatics and Pneumatics. But certain additional properties result from the *elasticity* of vapors and gases, which may be conveniently considered under the latter head.

523. *Vapors* are elastic fluids, which are produced from liquid or solid bodies, by the agency of heat, and which readily become liquid or solid again on the application of cold. Thus steam is raised from boiling water, and is again easily condensed by cold into the liquid state. *Gases* are permanently elastic fluids. They are never met with in nature either in the liquid or solid state, and it is only by means of extraordinary degrees of cold or pressure, that they can be made to give up their elasticity and become liquids. Atmospheric air is a body of this class; and since air and steam are, with slight exceptions, the only elastic fluids employed as mechanical agents, it is to these, chiefly, that our attention will be devoted.

524. The effects of Heat upon all bodies, are usually treated of in chemistry; but a few of those effects which are strictly mechanical, especially such as are produced on aëriform fluids, may be advantageously considered in this place.

The most general mechanical effect of heat is *expansion*. Heat expands all bodies, whether solid, liquid, or aëriform. *Aëriform bodies are expanded equally by equal additions of heat.** The in-

* This and various other propositions in Pneumatics, are proved by experiment. It is supposed that most of the Instructors who use this work, will have the means of illustrating or proving the truth of these

crease of volume is continued without limit, as the heat is augmented. The elasticity of a confined portion of air, as that contained in a close bottle or flask, for example, is uniformly increased by equal additions of heat. This is true of steam, however, only when the vessel is free from water; for, if steam is heated in contact with water, in a close vessel, its density and elasticity are *rapidly* increased, in a geometrical ratio, and its mechanical force shortly becomes so great as to burst almost any vessel that can be employed to contain it.

525. The properties of air may be exhibited under the form of a few simple propositions.

(1.) *Air is material.*

The two essential properties of matter are extension and impenetrability. (Art. 4.) That air has extension, needs no proof. That it is impenetrable, or has the property of excluding all other matter from the space which it occupies, is proved by experiment. Thus if we depress in water a tall jar, or a tumbler, we shall find that the water rises only through a certain *part* of the vessel, to whatever depth we immerse it; and if, to a hollow cylinder, made smooth and closed at the bottom, we fit closely a stopper or solid cylinder, called a piston, moving freely in it, on applying the piston, no force will enable us to bring it into contact with the bottom of the cylinder, unless we permit the air within it to escape. Two other properties exhibited by air, likewise indicate that it is material: these are *inertia* and *weight*. The inertia of air is manifested by the resistance it opposes to bodies moving in it; as, for example, an open umbrella moved through the air, in a direction parallel with the staff; and the weight of the air is shown by the fact that a vessel, as a bottle, from which the air has been withdrawn (by methods to be described hereafter) weighs less than before. A vessel of the capacity of a wine quart, weighs about eighteen grains less after the air is exhausted, than before. One hundred cubic inches of air weighs thirty grains and a half.

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propositions, by the aid of appropriate apparatus. But even when this is not the case, we conceive that very little benefit can accrue to the learner from the bare description of experiments.

(2.) *Air is a fluid.*

This property is manifested not only by the great mobility of its parts, but also by the distinguishing property of fluids, (Art. 445.) viz. that any portion of air at rest, presses and is pressed equally in all directions; and that a pressure or blow applied to any part, is propagated through the whole mass, and affects every part alike. (Art. 446.)

(3.) *Air is an* ELASTIC *fluid.* (Art. 117.)

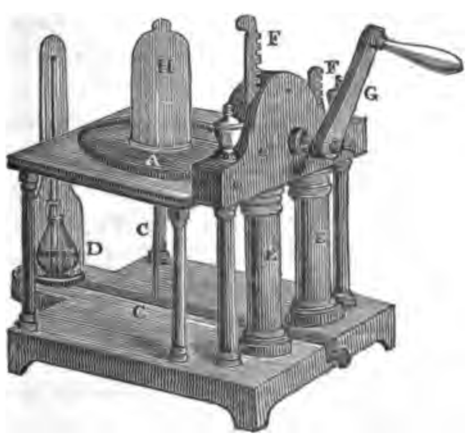
Thus, when an inflated bladder is compressed, it immediately restores itself to its former situation. Indeed, since air when compressed, restores itself, or tends to restore itself, with the same force as that with which it is compressed, it is a *perfectly elastic* body. (Art. 117.)

526. Before we proceed further, it is necessary for the learner to be made acquainted with the apparatus, by which the mechanical properties of air are illustrated.

The Air Pump.

The Air Pump is an instrument used for the purpose of exhausting the air from any given space. Though of several different forms,

Fig. 202.



yet the most common construction is that represented in fig. 202. The chief parts are the *plate* A, the *barrels* EE, and the *pipe* or

canal CC, leading from the plate to the barrels. The glass vessels which are set upon the plate, are called in general *receivers*. A *guage* is sometimes employed (as represented by D in the figure) to indicate the degree of exhaustion; but the nature of this appendage will be better understood hereafter. Such is the construction of the air pump in general; but the importance of this apparatus entitles it to a more minute description. In order, then, fully to understand the principle of the air pump, and other kinds of apparatus designed for producing a vacuum, we must understand the construction of *valves*, and of the *cylinder* and *piston*.

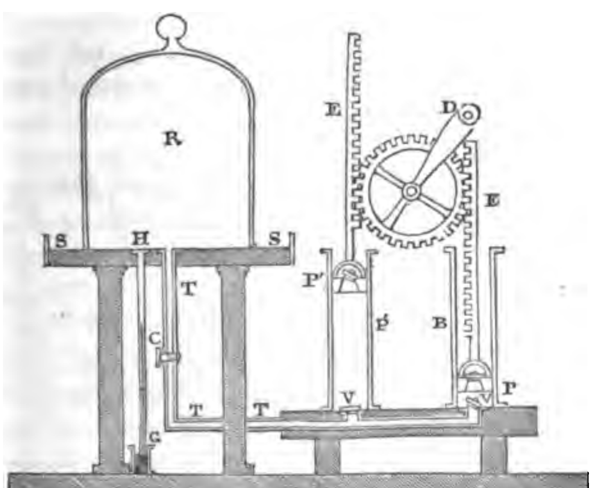
527. *A* VALVE *is a contrivance which permits a fluid to pass in one direction, but prevents its passing in the opposite direction.* The clapper seen on the under side of a pair of bellows, is a familiar example of a valve. The valve employed in the air pump, usually consists merely of a strip of oiled silk, tied over a small orifice. The air by pressing *outwards* from the orifice raises the silk, opens the valve, and makes its escape; while by pressing *inwards* upon the orifice, it keeps the strip of silk close to the orifice, and is therefore prevented from passing in that direction. The piston and cylinder are exemplified in a common syringe. It consists of a hollow cylinder, or barrel, to which is fitted a short solid cylinder called the piston, which is moved up and down the barrel by means of a projecting handle called the piston-rod, and is fitted so closely to the barrel as to be air tight. Suppose now that the cylinder is in a perpendicular position, closed below but open above, and that the piston rests on the bottom. On drawing up the piston, the air above it is lifted out, and the space below it is a vacuum. If a small orifice be made in the bottom of the barrel, then as the piston is drawn upwards, the air will flow in and no vacuum will be formed; and as the piston is depressed again, the air is forced back. But by attaching a valve to the orifice, we may admit or exclude the external air at pleasure. If the strip of silk be tied on the *outside*, then, on drawing up the piston, the air will not follow, but the piston will go up heavily, since it lifts up the entire weight of the column of air that rests upon it, (there being nothing below it to act as a counterpoise,) and if the hand be withdrawn from the piston rod, the piston will descend spontaneously. Again, if the valve be placed on the *inside*, then the external

air will follow the piston as it rises, and no vacuum will be formed. If now the piston be depressed, the air cannot be expelled, (since the valve closes on the orifice in that direction,) and the piston cannot be forced down to the bottom of the barrel, unless a valve is placed in the piston itself, opening outwards; in this case the air of the barrel may be expelled by depressing the piston.

528. We have been thus minute in the description of the construction of valves, and of the cylinder and piston, because when these things are clearly understood, the learner will easily comprehend the principle of the air pump, of the common house pump, of the steam engine, and of every other species of pneumatic apparatus. Let us now return to the *air pump.*

In the barrels, two pistons play up and down, each of which is furnished with a valve opening upwards into the open space, through which the piston rods move. Another valve is placed at the bottom of each barrel, opening into the barrel. The piston rods are indented bars, to which a toothed wheel (concealed in fig. 202, but seen in fig. 203) is adapted, which, being turned backwards and forwards by means of the winch G, (fig. 202.) alternately raises and depresses the two pistons, as is represented in the annexed figure. Suppose now

Fig. 203.



the receiver to be placed on the plate of the pump, one of the pistons being at the top, and the other at the bottom of the barrel. We turn

the winch, the piston rises, and the air of the receiver opens the valve at the bottom of the barrel, and diffuses itself equally through the barrel and the receiver. We turn the winch in the opposite direction, the piston descends, compresses the air in the barrel before it, which, as it cannot go back into the receiver, opens the valve in the piston itself, and escapes into the vacant space in which the arm of the piston moves. This process is repeated every time the piston rises and falls; and it is the same in both barrels, two being employed for no other reason than to accelerate the process of exhaustion.

529. *The exhaustion proceeds at a rate, which increases in a geometrical ratio.*

Suppose, for example, that the capacity of one of the barrels is just one-ninth part of that of the receiver, including that of the pipe which leads from the receiver to the barrel. When the piston is first raised from the bottom to the top, the air which previously occupied the receiver, expands so as to diffuse itself equally through the receiver and barrel. The barrel, therefore, will contain a tenth part of the whole of the enclosed air, and nine tenths will remain in the receiver. On depressing the piston, this tenth part is expelled through the piston valve. On elevating the piston, the air remaining in the receiver (which is nine tenths of the original quantity,) diffuses itself equally through the receiver and barrel, as before; consequently the barrel contains $\frac{1}{10}$ of $\frac{9}{10}=\frac{9}{100}$ of the original quantity, and $\frac{81}{100}$ remain in the receiver. By continuing this estimate, we should obtain the results expressed in the following table.*

Number of strokes.	Part of the air expelled at each stroke.	Part remaining in the receiver.	Whole quantity expelled.
1	$\frac{1}{10}$	$\frac{9}{10}$	$\frac{1}{10}$
2	$\frac{9}{100}$	$\frac{81}{100}$	$\frac{19}{100}$
3	$\frac{81}{1000}$	$\frac{729}{1000}$	$\frac{271}{1000}$
4	$\frac{729}{10,000}$	$\frac{6561}{10,000}$	$\frac{3439}{10,000}$
5	$\frac{6561}{100,000}$	$\frac{59049}{100,000}$	$\frac{40951}{100,000}$
6	$\frac{59049}{1,000,000}$	$\frac{531441}{1,000,000}$	$\frac{468559}{1,000,000}$
7	$\frac{531441}{10,000,000}$	$\frac{4782969}{10,000,000}$	$\frac{5217031}{10,000,000}$

* The estimate is made for a single barrel: in the double-barrelled air-pump, the rate of exhaustion will be just doubled.

530. The numbers in the first column denote the rate of exhaustion, and it is evident that they compose a geometrical series, the constant ratio being $\frac{9}{10}$. Also the quantities remaining in the receiver after each stroke compose a similar series, the ratio being the same. After seven strokes, the quantity remaining in the receiver is less than one half the original quantity. If we had taken a smaller receiver, the rate of exhaustion would have been much more rapid. Thus, if the receiver had only twice the capacity of the barrel, the series would have been $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$, $\frac{1}{32}$, $\frac{1}{64}$, $\frac{1}{128}$, $\frac{1}{256}$, $\frac{1}{512}$, $\frac{1}{1024}$; so that, with ten strokes of the piston, the air of the receiver would have been rarefied more than one thousand times.

531. As this series never terminates, it is evident that a complete exhaustion can never be effected by the air pump. Indeed, in practice, the vacuum is far less perfect than the theory would make it by the repetition of the blows of the piston; for when the air in the receiver becomes very much rarefied, it has not elasticity sufficient to raise the valve at the bottom of the barrel; or even if that difficulty is obviated by a different construction of the valve, still the difficulty of making the joints and valves perfectly air tight, is such as to impair the perfection of the void.*

532. By means of this instrument, we may obtain very striking illustrations of the mechanical properties of air.

(1.) The *pressure* of the air acts with great force on all bodies at the surface of the earth, amounting, as we shall show hereafter, to nearly 15 pounds upon every square inch, or more than 2000 pounds upon a square foot. Upon so large a surface, therefore, as that of the human body, the pressure amounts to no less than 13 or 14 tons; but being so uniformly distributed within and without, and on all sides,

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* Air pumps are of several different forms, varying in construction; but as it is our object in this work to consult brevity as much as possible, we content ourselves with explaining to the learner the most common form of this instrument, and the leading principles, leaving further details to be supplied by the instructor or lecturer.

it is, when the air is at rest, scarcely perceptible.* In consequence of this pressure, the air insinuates itself into all fluids, and fills the pores of all solids except the most dense, as gold or platina. The pressure of the air diminishes the tendency of fluids to pass into the state of vapor, and of course raises their boiling point. Warm water, at a temperature much below the boiling point, will be set a boiling under the receiver of an air pump, or in a vacuum formed in any other way. Indeed, if it were not for atmospheric pressure, water would require only the moderate heat of 72 instead of 212 degrees of heat to make it boil; and the more volatile fluids, as alcohol and ether, would hardly be found in nature, in the liquid state.

(2.) The *elasticity* of the air is such, that the smallest portion of it may be expanded beyond any known limits, by removing the external pressure. By this means, a bubble may be made to fill a very large space. On the other hand, air has been condensed by pressure, until its density has been greater than that of water, still retaining the elastic, invisible state.† In consequence of its elasticity, air is set in motion by the least disturbance of its equilibrium, whether by condensation or rarefaction, thus giving rise to the phenomena of winds.

(3.) Air is essential to the support of *combustion*, and to the *respiration* of animals; and finally, it is the principal medium of *sound*. It may be farther shown, that the weight of bodies is diminished by the buoyancy of air, (acting on the same principle as water, Art. 463,) and that light bodies are sustained in it, in consequence of its greater specific gravity, while, in a vacuum, bodies of various densities, as a guinea and a feather, fall towards the earth with equal velocities.

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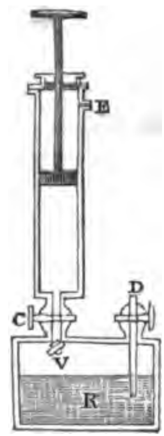
* Fishes are sometimes caught at the depth of 2600 or 2700 feet, where the pressure of the water is equal to 80 atmospheres, or more than 82 tons to the square foot; yet these fishes are not injured by such an immense weight, or sensibly impeded in their motions. (Camb. Mech. p. 352.)

† Gregory, I, 481.

533. These are the leading truths which are established and illustrated by means of the air pump, which the learner will better comprehend by witnessing the actual experiments, than by any description of them that could be offered.

534. The condensation of air is usually effected by means of the *Condensing Syringe.* This instrument is a cylinder and piston, the cylinder having a valve opening outwards, while the piston is without a valve. The principle of its operation will be readily understood from the figure. Near the top of the cylinder is a small hole in the side, which is immediately below the piston, when this is drawn up to the top of the cylinder. On forcing down the piston, the air is driven before it, and expelled through the valve at the bottom. By connecting a bottle or other close vessel with the bottom, the air expelled may be driven into that, its return being prevented by the same valve. The piston being drawn up again above the opening in the cylinder, another similar portion of air may be forced into the condensing bottle; and thus the process may be continued indefinitely.

Fig. 204.



535. The *Condensing Fountain* is a bottle, usually of copper, partly filled with water, upon the surface of which the air is condensed by means of the condensing syringe. The fluid being thus brought under a strong pressure, it tends to issue with great force whenever a pipe, that is inserted in the bottle, and extends below the surface of the water, is opened. The celebrated spouting springs of Iceland, called the *Geysers,* in which water accompanied by large masses of rock, is thrown to the height of 200 feet, arise from pneumatic pressure acting upon the surface of water in the interior of the earth, the aëriform substance, whatever it may be, being produced by means of volcanic action.

536. The *Air-Gun* is an instrument in which condensed air is substituted as the moving force instead of gun-powder. By means of a condensing syringe, air is strongly condensed in a metallic ball fur-

nished with a valve at the mouth, where it is screwed on the gun below the lock. As the lock is sprung, it falls upon a plug, and forces it upon the valve, which suddenly opens, and the air rushes into the barrel of the gun, and by its sudden expansion, propels a ball much in the same manner as gun-powder would do in its place.

537. The *Diving Bell* is an apparatus employed for exploring the depths of the sea. It was formerly made in the shape of a bell, but is now more commonly made square at the top and bottom, the bottom being a little larger than the top, and the sides slightly diverging from above. The material is sometimes cast iron, the whole machine being cast in one piece, and made very thick, so that there is no danger either from leakage or fracture. Sometimes the diving bell is made of planks of two thicknesses, with sheet lead between them. In the top of the machine are placed several strong glass lenses for the admission of light, such as are used in the decks of vessels to illuminate the apartments below.

538. The diving bell depends for its efficacy on that quality of air, which is common to all material substances, *impenetrability;* that is, the exclusion of all other bodies from the space it occupies. The principle may be illustrated by depressing a tumbler or jar in water, with the mouth downwards: it will be seen (Art. 525.) that the water will ascend so far as to occupy only a part of the capacity of the vessel, the upper part being occupied by air. As the diving bell descends in the water, the air inclosed in it is subject to its pressure, (which increases with the depth,) and by virtue of its elasticity, it will become condensed in proportion to this pressure. Thus at the depth of about thirty-four feet, the hydrostatic pressure will be equal to that of the atmosphere, and consequently, the air being under a pressure equivalent to that of two atmospheres, it will be condensed into one half its original volume. As the depth is increased, the space occupied by the air in the bell will be proportionally diminished. Seats are furnished for the workmen, and shelves for tools, and various other conveniences. Although at the depth of thirty-four feet, the water would occupy one half the capacity of the vessel, and more or less at different depths, yet by means of a forcing pump or condensing syringe communicating between the atmosphere above and the machine, through a pipe, air may be thrown in so as to exclude the wa-

ter entirely. By the same means fresh air may be conveyed to the workmen, the portion of air rendered impure by respiration being at the same time suffered to escape by opening a stop-cock in the top of the machine.*

539. Before we can proceed to the consideration of the atmosphere, it is necessary for the learner to become acquainted with another important instrument, the BAROMETER, by means of which, as well as by means of the air pump, our knowledge of the atmosphere has been greatly enlarged.

The Barometer.

Fig. 205.

Let us take a glass tube, about three feet in length, closed at one end and open at the other. We fill the tube with quicksilver, and invert it in a vessel of the same fluid. The column of quicksilver falls to a certain height, about twenty nine or thirty inches, where, after vibrating a few times, it remains at rest. The space in the tube above the quicksilver being void of air or any other substance, it is of course a vacuum, and is usually denominated the *Torricellian* vacuum, from Torricelli, an Italian philosopher, who first discovered this method of producing a vacuum. Various precautions are necessary, in order to preserve this space free from air or any aëriform substance: when these precautions are taken, this vacuum is the most complete of any that we can command.

540. The column of quicksilver is sustained by the pressure of the atmosphere, on the open mouth of the tube which is immersed in the same fluid;† and it must have the same weight with a column of the atmosphere of the same base, otherwise it would not be in equilibrium with it. We hence arrive at an accurate knowledge of the actual weight

* Lardner's Pneumatics.

† As young learners sometimes find a difficulty in conceiving clearly how the pressure of the air acts in this case, we subjoin a remark or

and pressure of the air, since it is equal to the weight of a column of quicksilver of the same base, thirty inches in length. The weight of such a cylinder of quicksilver is easily ascertained,* and it results, that the pressure of the air on every square inch of surface is, as stated in Art. 532, about 15 lbs. or more than 2000 lbs. upon a square foot. Since different fluids balance each other in opposite columns pressing base to base, when their heights are inversely as their specific gravities, (Art. 467.) a column of water in the place of the mercury would stand at the height of about 34 feet. For quicksilver being 13.57 times heavier than water, the latter column must be 13.57 times higher than the other; that is, $30 \times 13.57 = 407.1$ inches $= 33.84$ feet.

541. By observing from day to day the height of the column of quicksilver prepared as above, we shall find that it varies through a space of two or three inches, showing that the atmosphere does not always exert the same pressure, but that a given column of the air is sometimes lighter and sometimes heavier. This instrument, therefore, enables us to ascertain the relative weight of the air at any given time, and hence its name *barometer*.† For the purpose of indicating these variations with minuteness and precision, a graduated scale is attached to the barometer, divided into inches and tenths of an inch, and usually extending from twenty seven to thirty one inches, —a space which is more than sufficient to comprehend all the natural variations in the weight of the atmosphere.

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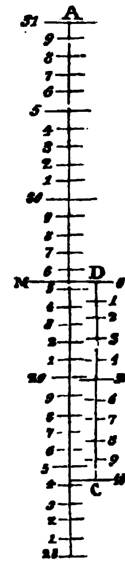
two. It must be recollected, that any impulse or pressure exerted on the surface of the fluid in the vessel, extends alike to every part of it; (Art. 446.) and since fluids act upwards as well as downwards, it is plain that the pressure acts in sustaining the column of mercury in the same manner as though it were applied directly to the mouth of the tube.

* Since a cubic inch of water weighs 252.525 grains, and quicksilver is 13.57 times heavier than water, therefore, a cubic inch of quicksilver weighs 3426.76 grains; and 30 inches weigh 102802.8 grains. But 7004 grains troy make one pound avoidupoise. Therefore, $\frac{102802.8}{7004} = 14.7$ lbs.

† From βαρος *weight*, and μετρον *measure*.

Fig. 206.



542. As these changes of weight are sometimes very minute, a contrivance called a *vernier* is attached to the scale, by means of which the tenth of a tenth, that is, the hundredth part of an inch may be estimated. The vernier consists of a small plate movable up and down by a screw upon the graduated part of the barometer, and is divided as follows. Calling the scale of the barometer B, and that of the vernier V, the divisions of B are one tenth of an inch, while those of V are one tenth larger, that is $\frac{1}{10}$ of $\frac{1}{10}$ $=\frac{1}{100}$ inch larger, ten of V making eleven of B. Now suppose the mercury stands at twenty nine inches, five tenths, and *a little more*. To ascertain the exact amount of this small excess, we bring the top of the vernier, whence the graduation begins, to coincide with the surface of the mercury. If the mercury be $\frac{1}{100}$ inch above 29.5, then we descend only one division of V, before we find it coinciding with B, (for it *gains* $\frac{1}{100}$ every division,) and the height of the mercury will be 29.51; if the mercury be $\frac{2}{100}$ above 29.5 then the *second* division on V will coincide with B, and the height of the mercury will be 29.52; and, in general, if, after bringing the top of V to coincide with the surface of the mercury, we look along down the scale until a division of V coincides with one of B, the number of that division of V denotes the number of *hundredths* to which the excess above the inches and tenths amounts.*

[The student is requested to describe the vernier from the annexed figure, and to read off the inches and hundredths.]

543. Since the variations of the barometer correspond to the variations in the weight of the air at the same place, and since these variations are connected with changes of weather, this instrument thus becomes a *weather glass*, and enables us, in certain cases, to foresee changes of weather. The most uniform indications of the barometer are, that *its rise denotes fair*, and *its fall denotes foul*

* Astronomical instruments have their scales graduated on the same principle, so as to indicate small fractions of a second.

weather, whatever may be its absolute height. Also, a *sudden and extraordinary descent* of the mercury attends, and frequently precedes, a *violent wind*. The immediate cause of the descent of the barometer, is undoubtedly a *rarefaction* of the air at that place; but the cause of this rarefaction itself, it may be difficult to account for. The consideration of this point will be resumed hereafter.

544. The mean pressure of the atmosphere, as indicated by the barometer, is nearly the same, at the level of the sea, in all parts of the earth, corresponding very nearly to 30 inches of mercury. This fact has been verified by numberless observations, made with the barometer in both hemispheres, from the equatorial to the polar regions. The following results for several places, in different latitudes, corrected for temperature, elevation above the level of the sea, and the influence of the earth's rotation on its axis, are nearly uniform.

	Latitude.	Bar. Pressure.
Calcutta, - - -	22° 35′ - -	29.776
London, - -	51 31 - -	29.827
Edinburgh, - -	55 56 - -	29.835
Melville Island, -	74 30 - -	29.884

But, though the mean pressure of the atmosphere is nearly the same, at the level of the sea, over the whole globe, the extent of the variations to which it is liable, is exceedingly different in different parallels of latitude. At the equatorial regions, the range of the barometer is much more limited than within the polar circles; and in the frigid zones, it is more limited than in the temperate. Within the tropics, the fluctuations of the barometer do not much exceed ¼ of an inch, while beyond this space, they reach to 3 inches.* The most extensive variations take place between the latitudes of 30° and 60°, being the zone in which the annual changes of temperature and humidity possess the widest range.†

545. Shortly after the invention of the barometer, it was observed that the mercury descends, when the instrument is carried to a more

* Daniell's Meteorology, I. 108.
† Ed. Encyc. art. "Physical Geography."

elevated situation. The descent is found to be about $\frac{1}{10}$ of an inch for 87 feet. From this observation, we may deduce the specific gravity of air compared with mercury or water; for $\frac{1}{10}$ of an inch of mercury has, it appears, the same weight as 87 feet, or 1044 inches, of air. Consequently, 1 inch of mercury weighs as much as 10440 inches of air; that is, mercury is 10440 times, and water is $\left(\frac{10440}{13.57}=\right)$ 769 times, heavier than air.

546. As the air pump enables us to investigate the mechanical properties of any portion of air, so the barometer enables us to study the properties and relations of the entire body of the air, that is, the atmosphere. By means of these two instruments, the following facts are well established.

(1.) *The space occupied by any given portion of air*, (as 100 grains, for example,) *is inversely as the pressure.* A weight of two atmospheres diminishes the bulk to one half; of three atmospheres, to one third; and of one hundred atmospheres, to one hundredth part of its former bulk.

(2.) As the density is likewise inversely as the space occupied, therefore, *the density is as the pressure.*

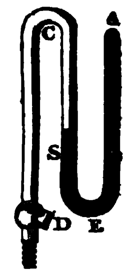
The learner is now prepared to understand the principles on which are constructed the several *gauges* used in connexion with the air-pump, *to indicate the degree of exhaustion.*

The gauge represented at D, Fig. 202. consists of a glass tube filled with mercury, and inverted in a small jar of the same fluid, and covered over with a receiver. This apparatus is placed upon the smaller plate of the pump, which is connected with the larger plate, by a horizontal pipe. Consequently, when the air in the receiver H is rarefied by working the pump, the air in the small receiver D, being rarefied in the same degree, will at length have its elasticity so much diminished, as to be unable to sustain even the short column of mercury in the tube. The mercury, therefore, will descend in the tube, and will approach towards the level of the fluid in the jar, and will come nearer to it in proportion as the exhaustion is more perfect.

The gauge exhibited in Fig. 203. G, (which is connected immediately with the receiver,) acts on a different principle. It consists of a tube, about 30 inches long, open at both ends, the lower end

dipping into a small vessel of quicksilver, and the upper end opening into the receiver. On turning the pump, the pressure is diminished on the upper surface of the mercury in the tube, and the external pressure of the atmosphere forces up the fluid to a height corresponding to the degree of exhaustion. A scale, graduated into inches and tenths, is attached to the tube.

Fig. 207.



The *syphon gauge*, represented in Fig. 207. is screwed upon the small plate of the pump, instead of the apparatus exhibited at D, Fig. 202. Previous to exhaustion, the quicksilver is sustained in the arm A of the tube by the atmospheric pressure. When this pressure is diminished to a certain extent, the column of quicksilver descends, and in a perfect exhaustion would attain the same level in both arms of the tube. Consequently, the nearer it approaches to that level, the better is the exhaustion.

(3.) Since air, when compressed, endeavors to restore itself, with a force which is equal to that which compresses it, (being when at rest in equilibrium with that force,) therefore, *the elasticity is as the density, and inversely as the space occupied.* In this proposition, the temperature is supposed to remain uniform. But, the bulk and density of a portion of air remaining the same, *the elasticity is as the temperature.*

547. Hence the elasticity of air may be increased either by compressing it, or by heating it in a confined state; and its elasticity may be diminished either by lessening the pressure, or by cooling it. The elasticity of springs is known to be frequently impaired by continued action. This is not the case with air. Air has been left for several years very much compressed in suitable vessels, in which there was nothing that could have a chemical action upon it; and afterwards, on removing the unusual pressure, and restoring the same temperature, the air has been found to recover its original bulk, which shows that the continuance of the pressure had not diminished the elasticity of it in the least perceptible degree.*

* Cavallo, II, p. 225.

The Atmosphere.

548. The knowledge now acquired of the properties of elastic fluids, will qualify the learner to enter advantageously upon the study of the entire body of the air, which constitutes the atmosphere. Let us therefore now proceed to consider its *weight*,—its *extent* and *density*,—its relations to *heat and moisture*, giving rise to the various phenomena of Meteorology,—and its relations to *sound*, whence arises the science of Acoustics.

549. The WEIGHT of the entire atmosphere may be easily estimated by means of the barometer; for, taking the medium height of the mercury at thirty inches, the weight of the atmosphere is equal to that of a sea of quicksilver, covering the whole earth to the depth of two and a half feet. This would add five feet to the diameter of the globe, and the contents of the whole mass of quicksilver, in cubic feet, would be equal to the difference between the solid contents of the globe, and those of a sphere of a diameter five feet greater. Having the number of cubic feet of quicksilver, we have only to multiply that number by the weight of one foot ($=13.57\times62\frac{1}{2}=848.125$ lbs.). The calculation proceeds as follows.

Let R denote the radius of the earth; r the height of the mercury; π the ratio of the circumference of a circle to its diameter, or 3.14159; the solidity of the globe $=\frac{4\pi R^3}{3}$;

Do. of the sphere, including the mercury $=\frac{4\pi(R+r)^3}{3}$;

Do. of the mass of mercury $=\frac{4\pi(R+r)^3}{3}-\frac{4\pi R^3}{3}=$

$4\pi(R^2r+r^2R+\frac{r^3}{3})$. But since r denotes but a very small fraction of R, the two last terms have so small a value, that they may be thrown out without materially affecting the result, and the contents of the mass of quicksilver will be $4\pi R^2r$. Substituting for these several quantities their numerical values, we have $4(3956\times5280)^2\times3.14159\times2.5=$ number of cubic feet in the mass of mercury; which being multi-

plied by 848⅛, gives 11,624914,803603,492864 lbs., or more than eleven trillions of pounds, or five thousand billions of tons.*

Were the atmosphere of equal density throughout, it would be easy to determine its height, since opposite columns of different fluids are in equilibrium, when their heights are inversely as their specific gravities. (Art. 467.) Therefore, as the specific gravity of air is to that of quicksilver, so is the height of the column of quicksilver to the corresponding height of the column of air that balances it. That is, 1 : 10440::2.5 : 26100 feet =5 miles nearly.

550. But the atmosphere is very far from being throughout of uniform density. Several causes conspire to produce this result. 1. The different quantities of superincumbent air at different altitudes; 2. The decreasing attraction of the earth in proportion as the square of the distance from its center increases; 3. The influence of heat and cold; 4. The admixture of vapors and other fluids; 5. The attraction of the moon and other celestial bodies.† That the lower strata of the atmosphere are far more dense than the upper, will be obvious from this consideration, that the portions which rest on the surface of the earth, sustain the weight of the whole body of the atmosphere, which, as appears from Art. 549, is immensely great. But the density of air is as the compressing force. (Art. 546.) As we ascend from the earth, the weight sustained is constantly diminished, and the density lessened, according to the following law.

551. *The densities of the air decrease in a geometrical, as the distances from the earth increase in an arithmetical ratio.*

Demonstration.—Let us suppose that the strata of air are taken so thin, that the density of each may be considered as uniform throughout. Let the density of the inferior stratum be A, that of the second B, of the third C, and so on. Moreover let a be the weight of the whole column of the atmosphere resting on A; b the weight of the

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* A less accurate method of finding the weight of the atmosphere, is to multiply the number of square inches on the surface of the globe by fifteen pounds.

† Cavallo, I, 227.

column when A is taken away; c its weight when A and B are subtracted, and so on. Then the weight of the first stratum is $a-b$, that of the second, $b-c$, &c. Now the densities of two bodies of the same volume are as their weights. Therefore, $A : B :: a-b : b-c$. But since the densities are as the pressures, (Art. 546.) and the pressures are the weights of the incumbent columns, therefore, $A : B :: b : c$. Hence $a-b : b-c :: b : c \therefore ac-bc=b^2-bc \therefore ac=b^2 \therefore a : b :: b : c$; that is, the weights and consequently the densities of the successive strata form a geometrical series. If, therefore, at a certain distance from the earth, the air be twice as rare as at the surface of the earth, at twice that distance it will be four times as rare, at three times that distance, nine times as rare, &c.

552. By observations on the barometer at different altitudes, aided by calculation, it is ascertained, that at the height of seven miles above the earth, the air is only one fourth as dense as it is at the surface.* Hence if we take an arithmetical series, increasing by seven, to denote different heights, and a geometrical series whose constant multiplier is one fourth, to denote the corresponding densities, we may easily ascertain the density of the air at any proposed elevation.

Arithmetical series,	7	14	21	28	35	42	49
Geometrical series,	$\frac{1}{4}$	$\frac{1}{16}$	$\frac{1}{64}$	$\frac{1}{256}$	$\frac{1}{1024}$	$\frac{1}{4096}$	$\frac{1}{16384}$

From this table it appears, that at the height of twenty one miles, the air is sixty four times as rare as at the surface of the earth; at the height of forty nine miles, sixteen thousand three hundred and eighty four times as rare; and if we pursue the calculation, we shall find that its rarity at the moderate distance of only one hundred miles, is one thousand millions of times greater than at the earth,† and of course would oppose no sensible resistance to bodies revolving in it. De Luc ascended in a balloon to such a height that his barometer fell to twelve inches. Supposing the barometer at the surface to have stood, at that time, at thirty inches, it follows that he must have left three fifths of the whole atmosphere below him; for six inches being

* Cotes. Hyd. Lect. p. 103.

† Rees' Encyc. Art. "Atmosphere."

one fifth of thirty, twelve inches must be two fifths, and consequently three fifths of the whole must be below. His elevation was upwards of twenty thousand feet.*

If there were an opening into the interior of the earth, which would permit the air to descend, its density would increase in the same manner as it diminishes in the opposite direction. At the depth of about thirty four miles, it would be as dense as water; at the depth of forty eight miles, it would be as dense as quicksilver; and at the depth of about fifty miles, as dense as gold.

553. The foregoing law, however, does not afford *exact* data for estimating the density of the air at any given elevation, since the density is affected by the several other circumstances mentioned in article 550, which are not here taken into the account. Since the force of attraction diminishes as the square of the distance from the center of the earth increases, this diminution will occasion a corresponding decrease of density. However, as the force of attraction will be very nearly the same at such elevations as the highest mountains, as at the general level of the earth, (Art. 12.) no allowance is made on this account for barometric measurements, except in cases when extreme accuracy is required. Changes of temperature produce a much greater effect, since heat expands and cold contracts the air; and therefore, in estimating altitudes, the state of the thermometer is always to be taken into the account, in connexion with the height of barometer. Heat and cold also affect the height of the mercury in the barometer, independently of the pressure of the atmosphere without, and therefore it becomes necessary to reduce the observations to a fixed standard of temperature.

554. Owing to these different causes of irregularity in the density of the air at different elevations, it becomes a problem of much nicety and difficulty to obtain accurate measurements of heights, by means of the barometer; but the importance of the subject has led men of science to bestow very great attention upon it. We have room on-

* Lardner's Pneumatics, Sec. 144.

ly to indicate the *general principles* on which such measurements depend, leaving the details to treatises of greater extent.*

555. With regard to the *actual height of the atmosphere* above the earth, it is a point not easily determined. Efforts have been made to ascertain its height by means of the twilight; but the student is not prepared to judge of the accuracy of this method, without a knowledge of Optics and Astronomy. The consideration of it therefore, belongs to a subsequent part of our course of instruction. We merely remark here, that no great reliance is placed upon this method by those who are most competent to judge of it.

If the decreasing densities of the air as we ascend from the earth were accurately expressed by a geometrical series, (Art. 552.) it is obvious that such an atmosphere would be unlimited, since such a series would never end. But several considerations render it probable, that the atmosphere is bounded by definite limits. Such are the following: (1.) The heavenly bodies move in void spaces; otherwise they would meet with a resistance which would retard their motions, and the periods of their revolutions would not be unalterable as is found to be the case. (2.) The expansion of air is owing to a mutual repulsion between its particles. This force is diminished as the particles are removed farther asunder, by the enlargement of its volume; and we may conceive the repulsive force to be so much diminished at a certain distance from the earth, as to be counterbalanced by gravity, which being inversely as the square of the distance from the *center of the earth*, is nearly the same at all distances within a few miles of the earth's surface. (Art. 12.)† (3.) The con-

* The necessary rules for barometric measurements may be found in Robison's Mechanical Philosophy, Vol. III; Cavallo's El. Nat. Phil. Vol. II; Gregory's Mechanics, Vol. I; and in most of the Encyclopedias under the article *Barometer*.

† This argument takes it for granted that the air consists of indivisible atoms; for, were the air infinitely divisible, there would be no such *increase of distance between the particles*, and consequent diminution of repellent force, as is here supposed. But the existence of such atoms has been rendered extremely probable, and the conclusions deduced from the suppositions of such atoms, are found to accord

densation produced by extreme cold, such as is known to exist in the upper regions of the atmosphere, will oppose the expansion of the air, and counteract its enlargement of volume beyond a certain limit.

556. As we ascend from the earth, the temperature of the air constantly diminishes until we arrive at a region of frost, the lower limit of which is called the *term of perpetual congelation.* The heights of the term of congelation for every parallel of latitude from the equator to the north pole, have been computed, partly from observation, and partly from the known mean temperature of each parallel, and the decrement of heat as we ascend in the atmosphere; and the result is expressed in the following table :—

Latitude. °	Mean height of the term of congelation in feet.	Differences for every 5 deg. of latitude.
0	15577	
5	15455	122
10	15067	388
15	14498	569
20	13719	779
25	13030	689
30	11592	1438
35	10664	928
40	9016	1648
45	7658	1358
50	6260	1398
55	4912	1348
60	3684	1238
65	2516	1168
70	1557	959
75	748	809
80	120	628

From this table it appears, that the height of the region of perpetual frost at the equator is almost three miles; at the parallel

well with experience. (See Wollaston on the Finite Extent of the Atmosphere.—Phil. Trans. for 1822.)

of 35°, about two miles; and at the latitude of 54°, about one mile; while at the latitude of 80°, this region approaches very near to the earth, and at the pole it probably comes nearly or quite down to the earth. It is farther to be remarked, that the different heights decrease very slowly as we recede from the equator, until we reach the limits of the torrid zone, when they decrease much more rapidly, the maximum being at the parallel of 40°. The average difference for every 5 degrees of latitude from 30° to 60°, is 1334, while from the equator to 30°, the average is only 509, and from 60° to 80°, it is only 891. Important meteorological phenomena depend on this fact.

557. *What is the cause of the cold that prevails in the upper regions of the atmosphere?*

It is found by experiment that radiant heat, like that of the sun, passes through a transparent medium without obstruction, and consequently does not heat that medium.* Were the air perfectly transparent, the heat of the sun would scarcely affect it at all; but the vapors, clouds, and other substances that diminish the transparency of the atmosphere, intercept a certain portion of the sun's rays. In general, however, the manner in which the air receives the heat of the sun is this: the sun's rays first communicate their heat to the surface of the earth; the stratum of air next to the earth imbibes a portion of this heat and rises, while colder currents descend or flow in laterally, which in turn become heated and rise. Hence from the ground, when heated by the sun, a current of air is constantly ascending. On the other hand, in the absence of the sun, the ground loses its heat by radiation, and becomes colder than the air immediately above it. The air therefore now imparts a portion of its heat to the ground, is condensed, and remains in contact with the ground unless removed, as is commonly the case, by winds. The atmosphere, therefore, is, for the most part, heated and cooled *indirectly* by coming in contact with the surface of the earth.

558. The changes of temperature induced on the earth's surface by the sun's heat, are not sufficient to rarefy the air to any great ex-

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* Black's Lectures on Chemistry, Vol. I.

tent. A part, moreover, of the heat received from the earth in the day time, is restored to it again at night; hence the rarefied portions of air do not ascend far above the earth until they find their equilibrium.

As a portion of air rarefied by heat at the earth's surfaee ascends, the diminishing pressure which it sustains as it rises, has a tendency to enlarge its volume. But on the other hand, an enlargement of volume, increases its capacity for heat, and lowers its temperature, which tends to condense it. At a moderate elevation above the earth, these causes operate to keep the air at rest, and thus the heat of the earth is incapable of raising the temperature of the air, except within a moderate distance, beyond which the region of frost prevails, and the cold continues to increase, until it probably reaches, at a comparatively moderate distance from the earth, an intensity almost inconceivable.

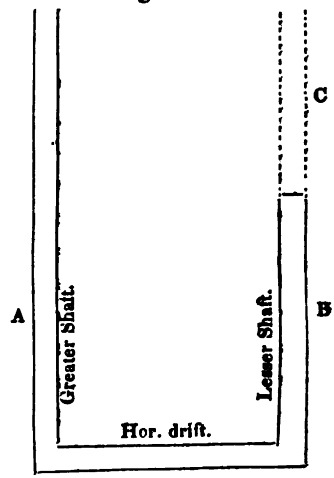
Relations of Air to Heat and Moisture.

559. Air is set in motion by every cause which disturbs its equilibrium. It is more sensible than the most delicate balance, and moves with the slightest inequalities of pressure.

Air is put in motion by *the least change of temperature.* Heat rarefies it, and, as intimated in article 557, renders it specifically lighter than the neighboring portions, and it ascends, while colder and denser portions flow in to restore the equilibrium. On the other hand, if air be condensed by cold, it descends, or flows off, until it meets with air of the same density, where it rests. These effects naturally result from the perfect fluidity and elasticity of this substance.

560. An illustration of this principle is seen in the manner in which air circulates in the shaft or pit of a deep mine. Such a circulation is kept up briskly, even amounting sometimes to a strong wind, when two shafts or pits of unequal heights are made to communicate with each other by means of a horizontal gallery, called a drift. The earth remains nearly at the same temperature summer and winter, while the external air is hotter in summer and colder in winter, than that within the mine. Now were the air within the earth

Fig. 208.



and without, of the same density, then the air of the two shafts and of the drift would remain in equilibrio, (Art. 456.) the longer shaft A, being counterbalanced by the shorter shaft B, extended so as to embrace C, a portion of the external air, to the same height as the column A. But suppose it summer; then the air in A, becoming condensed by the influence of the colder earth, is rendered specifically heavier, and overpowers the columns B and C, the latter consisting of air more rarefied than that within the earth. Hence the air will flow down the longer, and out of the shorter shaft; and by bringing all parts of the mine into the circulation, the whole interior will be ventilated. Again, suppose it winter; then the air in the longer shaft being warmer and more rarefied than the compound column BC, the latter preponderates, and the air flows in the opposite direction; namely, down the shorter and out at the longer shaft. In spring and autumn, when the temperature of the atmosphere and the mine are nearly equal, the miners complain much of the suffocating state of the air.*

561. The contemplation of the motions of the atmosphere on a large scale, as they exist in nature, leads to the subject of Winds; but we may see the same principles exemplified in *chimnies* and *fire-places*. A chimney may be regarded as a perpendicular tube, containing a column of air. Since the density of the air is less above than below, (Art. 551.) and consequently the resistance less at the top than at the bottom of the chimney, the tendency of any current of air through the tube is upward, flowing in the direction in which the resistance is least. When the air of the chimney is rarefied by heat from the fire-place, the cold air from below makes its passage upwards into the partial void, and thus supplies air to the fire to support its com-

* Robison's Mechanical Phil. III. 763.

bustion, and carries up along with it the smoke and vapors which proceed from the fire. The smoke, it will be remarked, is carried up, mechanically, by the ascending current of hot air; for smoke is itself heavier than air, and sinks or descends when not thus supported.* The *draught* of the chimney, or the strength and velocity of the ascending current, is influenced by several circumstances. (1.) Long chimnies have a stronger draught than short ones, because they present a longer column of rarefied air; but they may be so long as to cool the air too much before it has reached the top, in which case the smoke falls by its greater specific gravity. Long horizontal pipes, connected with fire-places or stoves, are apt to smoke, for a similar reason. (2.) A narrow throat, opening into a large pipe or funnel, makes a strong draught, because the velocity of the ascending current is thus increased, it being in different parts of the chimney inversely as the area of the section. (Art. 484.) The throat of the chimney, however, must be wide enough to admit freely all the mixed products of the ascending current, including the rarefied air, smoke, watery vapor, and so on; and, consequently, a wider throat is required for green wood than for dry, and least of all for anthracite coal, where the amount of volatile substances expelled from the fuel is comparatively small. (3.) A fire-place with a low front or breast, has a strong draught, because, in this case, no air can enter the chimney, except such as has felt the influence of the fire, and is thus fitted to keep the chimney warm; whereas, if the throat of the fire-place is high, much of the air that flows into it is cold and cools the chimney, and of course diminishes the degree of rarefaction in it. Moreover, when the throat is near the fire, it becomes more intensely heated, and thus the degree of rarefaction of the current of air that passes through it is augmented and its velocity increased. In the structure of fire-places and stoves, it is an important principle, that *as little air as possible should get into the flue of the chimney, except what passes through the fire;* and it is another important principle, in regard to the economy of fuel,

* This fact is illustrated by an experiment, suggested by Dr. Franklin, viz. by blowing the smoke of a tobacco pipe through water in a tumbler. The smoke, being cooled by this process, rests upon the surface of the water.

that *no more air should traverse the fire than what is necessary to support the combustion.* All the air that passes through the fire, over and above what undergoes decomposition, cools it, and carries a portion of the heat up chimney. It is obvious that the air of an apartment must be denser than that at the top of the chimney, otherwise the current will flow downwards, as is sometimes the case when the room is very close, and the throat of the fire-place so large as to require a great quantity of air to fill the rarefied space, in which case, the air of the room is speedily exhausted. Hence, the advantage, in close apartments, of small fire-places, or stoves which require but a small supply of air.*

562. But a much more extensive operation of the same principles is exhibited to us by nature, in the phenomena of WINDS. Rarefaction by heat and condensation by cold are the chief causes of winds. Their distinct existence and modes of operation, can frequently be discovered; and, in cases where we can discover neither, we are authorized to infer the presence of such a cause, since it is so constantly connected with the same effects in very numerous examples that daily pass before our eyes, while we are unacquainted with any other adequate causes of the same phenomena. The motion of the air, however, producing a wind, may be merely *relative*, arising from the motion of the spectator. Thus a steam boat, moving at the rate of sixteen miles an hour in a perfect calm, would appear to one on board to be facing a wind, moving at the same rate in the opposite direction; or if, in the diurnal revolution of the earth on its axis, any point of the earth's surface should move faster than the portion of the atmosphere above it, a relative wind in the opposite direction would be the result. (Art. 258.) The *direction* of the wind may be modified by various causes, the actual direction being the *resultant* of two or more currents which meet from different directions, or of several different forces. (Art. 65.)

563. *Land and sea breezes* afford a striking exemplification of the principle in question. These winds prevail in most maritime coun-

* See Dr. Franklin's Remarks on the Causes and Cure of Smoky Chimnies, *Works*, Vol. II, p. 256. Also, Count Rumford, *passim*.

tries, but more especially in the islands of the torrid zone, blowing off from the land at night, and towards the land in the day time. If we place a hot stone in a room, (says Dr. Robison,*) and hold near to it a candle just extinguished, we shall see the smoke move towards the stone, and then ascend up from it. Now, suppose an island receiving the first rays of the sun in a perfectly calm morning; the ground will become warm, and will rarefy the contiguous air. If the island be mountainous, this effect will be more remarkable; because the inclined sides of the hills will receive the heat more directly. The midland air will therefore be most warmed; the heated air will rise, and that in the middle will rise fastest; and thus a current of air upwards will begin, which must be supplied by air coming in on all sides, to be heated and to rise in its turn; and thus the morning sea breeze is produced, and continues all day. This current will frequently be reversed during the night, by the air cooling and gliding down the sides of the hills, and we shall then have the land breeze.

564. The *trade winds* afford an example of the operation of the same causes on a still greater scale. These winds prevail in the torrid zone and a little beyond it, extending to nearly 30° on both sides of the equator. When not affected by local causes, they blow constantly at the same place, in one and the same direction, throughout the year. Their general direction is from north-east to south-west on the north side of the equator, and from south-east to north-west on the south side of the equator. They owe their origin to the combined agency of two causes, namely, the movement of the air on either side of the equator, northward or southward towards the place of greatest rarefaction, and the westerly tendency arising from the effect of the earth's diurnal rotation on its axis,† since they do not instantaneously acquire the greater velocity which the equatorial regions have in consequence of the earth's revolution on its axis.‡ The duration

* Mech. Phil. III, 763.

† See Vol. I, p. 58, *Problem* 4.

‡ For a more extended description respecting the causes of the trade winds, see Daniell's Meteorology, p. 455, and American Journal of Science, Vol. XIX.

of the trade winds is variously modified in different parts of the world, but always in such a manner, that they blow towards the point of greatest rarefaction, and receive a relative motion from the effect of the earth's diurnal rotation.

565. The foregoing atmospheric phenomena arise chiefly from the relations of air to *Heat;* we are next to trace a few of the leading phenomena, which result from the relations of air to *Moisture.*

By the action of the sun's heat upon the surface of the earth, whether land or water, immense quantities of vapor are raised into the atmosphere, supplying materials for all the water that is deposited again in the various forms of dews, fog, rain, snow, and hail. Our limits will not allow us to enter largely into Meteorology, under which head, the various phenomena of the atmosphere are included, but we shall be able barely to glance at the subject.

566. The leading principle upon which the precipitation of moisture from the atmosphere, under any form, depends, is the following:—

The capacity of air for moisture is increased by heat and diminished by cold.*

In other words, air by being heated is rendered capable of *taking up* and *holding* a greater quantity of water in the invisible state, and by being cooled, its power of thus holding water is lessened.

Again, the capacity of air for moisture increases *faster than the temperature;* so that the addition of ten degrees of heat to air alrea-

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* The term *capacity* being frequently employed in the physical sciences, it is important for the student to obtain clear and correct views of its meaning. The power of a sponge to hold water, to stow it away in the interior, so as to render it invisible, is the *capacity* of the sponge for water. This capacity is capable of increase or diminution. Take a piece of dry sponge, and soak it in water; as its volume enlarges, its capacity for water increases—remove it from the water, and squeeze it gently; a part of the water runs out—suffer it to expand and it appears nearly dry; squeeze it again, and it becomes wet. Hence we say its capacity is increased by an enlargement of volume, and diminished by compression.

dy at the temperature of 70°, will increase the capacity for water much more than the same addition would do to air at the temperature of 40°. On the other hand, the cooling of hot air, diminishes its capacity for moisture much faster than the cooling of air already cold.

567. *Dew is formed when the air comes in contact with a surface in a certain degree colder than itself.* This is the simplest deposition of moisture from the atmosphere. Thus dew is formed copiously on a cup of cold water during summer, particularly before a thunder shower; because then the air is hot, and saturated with moisture, a portion of which it deposits as soon as it is cooled, its capacity for moisture being thus diminished. It is ascertained by actual observation that on those nights when copious dews occur, the ground becomes twelve or fourteen degrees colder than the air a few feet above it.* Consequently whenever the air, by circulating over the surface of the ground, comes in contact with this colder surface, it deposits a portion of moisture upon it. The quantity actually deposited will of course be greater as the difference of temperatures between the air and the ground is greater, and the air is more nearly saturated with moisture.

Dew is found to be deposited on different substances unequally,—more on vegetables than on dry sand; very little on bright metallic surfaces; and none at all on large bodies of water, as the ocean. In all cases, however, these surfaces are observed to maintain a corresponding difference in the temperature they acquire, some growing much colder than others equally exposed, while the surface of the ocean remains at the same temperature as the air incumbent on it. The air therefore sustains no reduction of capacity by circulating upon it, and no dew is deposited.†

568. *Fogs are produced by watery vapor coming in contact with air colder than itself.*

The vapor may be such as is just rising from the ground, or such as before existed in a body of common air that meets and mixes with

* Wells on Dew. † Ibid.

the colder air. Thus, in a cold morning, smoke proceeds from various moist substances, as from the breath of animals, from a hole in the ice of a river, from wells, and from many other sources. In each case, the vapor meets with cold air, which having so small a capacity for moisture, is unable to hold it in solution, and it is deposited in the form of fog. A striking example of fogs is seen over rivers, particularly in a summer morning, marking out their courses for a great distance. Here, since the temperature of the water changes but little during the night, while the neighboring land, and of course the air over the land, has become cold, the vapor which rises from the river during the night, and meets with cold air, is condensed into a fog. The fogs formed over shoals and sand banks, as the banks of Newfoundland, are deposited from the warm and humid air of the ocean, which is cooled by mixing with the cold air over the banks. Fogs are phenomena of cold climates, and are not so common in hot countries; the air in such situations having too great a capacity for moisture, to permit it to condense into a fog near the surface of the earth.

569. *Clouds are dependent on the same principle as fogs, consisting of vapor condensed by the cold of the upper regions.* They are formed over water, or moist places, by vapor rising so high, as to reach a degree of cold sufficient to condense it; or they result from the mixture of warmer with colder air, proceeding always from the warmer portion.

570. *Rain is produced by the sudden cooling of air, charged with large quantities of watery vapor.*

Suppose two bodies of air, a hotter and colder portion, both saturated with moisture, to meet; the compound would assume a temperature which was the mean between the two; but the quantity of heat which the colder portion of air would gain, would not increase its capacity so much as that of the warmer body would be diminished, by the loss of the same portion of heat. (Art. 566.) Hence the capacity of the mixture would be less than the average capacities of the separate portions, and consequently water would be deposited.*

* Hutton, in Ed. Phil. Trans. I. 41.

If the separate portions of air are not completely *saturated* with moisture, still the capacity of the mixture may be so much less than that of the constituents, as to render it unable to hold all the water they contained; and in this case, more or less water would be deposited.

571. This view of the general cause of rain, (which is commonly called Hutton's Theory of Rain, from Dr. Hutton of Edinburgh, who first proposed it,) is capable of being confirmed by an extensive induction of facts, by which it would appear, that *variable* winds, favorable to the mixture of air of different temperatures are accompanied by rain, while *constant* winds are accompanied by dry weather.

572. *Hail is produced by the mixture of exceedingly cold air, with a body of hot and humid air.** The cold wind is supposed to be derived from an elevation considerably above the term of perpetual congelation, and to be suddenly transferred to a body of hot and humid air, from which it precipitates the hail. Or it may be supposed to result from a hot wind blowing from the torrid regions into the limits of perpetual frost, and thus having its watery vapor suddenly congealed. Or it may be the product of the meeting of a very cold with a very hot wind. All that the theory requires, in order that hail should be precipitated, is, that *very hot* and *very cold bodies of air* should be mixed in any way whatsoever. Accordingly, hail is found to be most frequent and violent in those regions where hot and cold bodies of air are most easily mixed. Such mixtures are rarely formed in the torrid zone, since there the portion of *cold air* would be wanting; and a similar difficulty exists in the frigid zone, for there the *hot air* is wanting; but in the temperate climates, the heated air of the south, and the intensely cold winds of the north, may be much more easily brought together; and, accordingly, in the temperate zones it is, that hail-storms chiefly occur. Even in these climates they are most frequently found in places, where such mixtures are most easily formed, as in the south of France, lying, as it does, between the Pyrennees and the Alps, which are covered with perpetu-

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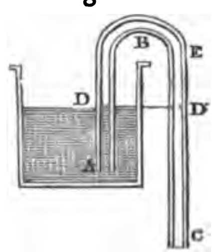
* See some remarks on Hail Storms, by the compiler of this work, in the Am. Jour. Science, Vol. XVIII.

al snows, while the intervening country is subject to become highly heated by the summer's sun, or is even visited, especially at a certain elevation, by occasional blasts of the hot winds that cross the Mediterranean.

Mechanical Agencies of Air and Steam.

573. In consequence of our power of forming a vacuum, either by the exhaustion of air or by the condensation of steam, and of directing the force with which these elastic substances rush into a void or press towards it, air and steam become important agents or prime movers, in various kinds of machinery. Many of the most useful machines involve in their construction the principles of both hydraulics and pneumatics, and therefore we have reserved an account of such machines to the present section.

Fig. 209.



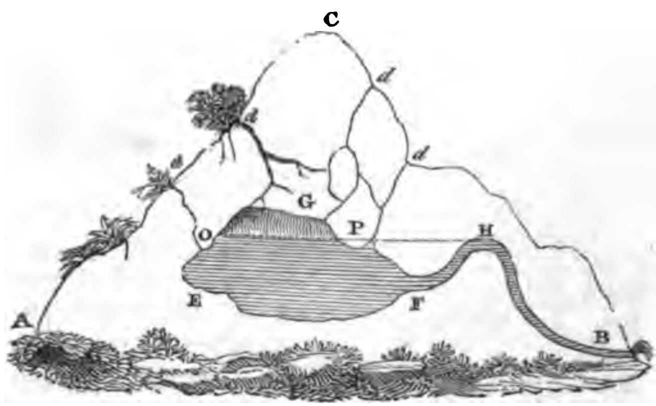
574. THE SYPHON.—If a tube having two arms, a longer and a shorter, be filled with water,* and the mouth of the shorter arm be immersed in water, the fluid will run out through the longer arm until the whole contents of the vessel are discharged. Such a tube is called a *syphon*. It may be filled with the fluid, either by suction or by pouring water into it, keeping the two orifices closed until the shorter arm is immersed. Or, when the syphon is large, each orifice is plugged, and water is poured in through an opening in the top of the bend. The opening being closed, the shorter leg is placed in the cistern, and the plugs removed, the fluid is discharged as usual. The *principle* of the syphon is as follows. The atmosphere presses equally on the mouths of both arms of the tube; but this pressure on each orifice is diminished by the weight of the column of water in the leg nearest to it; consequently, more of the atmospheric pressure is overcome by the longer than by the shorter column, and therefore the *effective pressure*, (or what remains,) is less at the mouth of the longer than at that of the shorter column, and the fluid runs in that direction

* Or any other liquid.

in which the resistance is least. All this will be obvious by inspecting the figure.*

Were the shorter column thirty four feet in height, it would counterbalance the entire pressure of the atmosphere on the surface of the fluid, and consequently, there would be no force remaining to drive the water forward through the tube. The syphon, therefore, can never raise water to a greater height than thirty four feet, nor quicksilver higher than about thirty inches. It is obvious, also, that the place of delivery, that is, the mouth of the longer arm, must be at a lower level than the surface of the water in the reservoir; so that this instrument cannot be used for elevating, but only for decanting fluids, or transferring them from one vessel to another. Its chief use is by grocers, in transferring liquors from one cask to another.

575. *Intermitting Springs*, or springs which flow freely for a time, and then cease for a certain interval, when they flow again, are explained on the principle of the syphon. The annexed cut represents



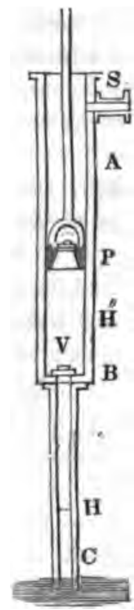
a reservoir or hollow in the interior of a hill, having a syphon-shaped outlet. It is obvious, upon hydrostatic principles, that no water will be discharged until the fluid has reached a level in the reservoir equal to the top of the bend in the outlet. Then it will begin to run out,

* We prefer to describe such instruments *in general terms*, but the student will find it convenient to recite the explanation from the figure, and letters are annexed to the figures for that purpose.

and will continue to run, until the water has descended to the level of the outlet; after which, no more water will be discharged until enough has collected to reach the higher level, as before.

576. The common Suction Pump.—This pump consists of two hollow cylinders, placed one under the other, and communicating by a valve which opens upwards. The lower cylinder (which has its lower orifice under water) is called the *suction tube.* In the upper cylinder, a piston moves up and down from the bottom to a spout in the side near the top. This cylinder we call the *exhausting tube.* Suppose, at the commencement of the operation, the piston is at the bottom of the exhausting tube, in close contact with the valve. On raising it, the air in the suction tube having nothing to resist its upward pressure, lifts the valve and expands, so as to fill the void space, which would otherwise be left in the lower part of the exhausting tube. By this means, the air in the suction tube is rarefied, and no longer being a counterpoise to the pressure of the atmosphere on the surface of the well, the latter predominates and forces the water up the tube until enough has been raised exactly to counterbalance the excess of the elasticity of the external air above that of the tube. As the piston descends, the air below it is prevented from returning into the suction pipe by the valve which closes on its mouth, but escapes through a valve in the piston itself opening upwards in the same manner as in the barrels of the air pump. (Art. 525.) The piston being raised again, the column of water ascends still higher, until it makes its way through the valve into the exhausting pipe. Then as the piston descends, the water opens its valve, and gets above the piston, and is lifted to the level of the spout, where it is discharged.*

Fig. 211.



* The student is requested to describe from the figure. It is recommended to him, however, to form as distinct an idea as possible, of the principle of a machine from the general description, before he resorts to the figure.

The principle of the suction pump may therefore be thus enunciated:

The water is raised into the exhausting pipe by the pressure of the atmosphere, and thence lifted to the level of the spout by means of the piston.

Since a column of water thirty four feet in height, in the suction tube, would counterbalance the entire pressure of the atmosphere on the surface of the well, no force would remain to urge the column any higher, and therefore the valve at the top of the suction tube, must be less than thirty four feet above the well.

517. Let us now consider the force which is required in each stage of the process, to elevate the piston, exclusive of the weight of the piston, rods, and the effects of the friction. Let the piston be at V, and the level of the water in the suction pipe at H. Let the number of feet in CH be called h. The elastic force of the air in BH will then be such as to exert a pressure on every square inch, equal to the weight of a column of water, whose base is a square inch, and whose height expressed in feet, is $34-h$. In its ascent, therefore, each square inch of the section of the piston, is pressed upwards by this force. It is, on the other hand, pressed downwards by the whole force of the atmosphere, which is equal to the weight of a column of water of the same base, and thirty four feet high. The effective force then which resists the ascent of the piston, for every square inch, is the weight of a column of water, whose base is a square inch, and whose height is the difference between thirty four feet, and $34-h$ feet; that is, the effective force is h feet. Thus it appears, that it requires a force to lift the piston exactly equal to the weight of a column of water, whose base is equal to the section of the piston, and whose height is that of the water in the suction pipe, above the level of the water in the well. It follows, therefore, that as the water rises in the suction pipe, the force required to lift the piston is proportionally increased.

Let us next consider the force required to lift the piston, in the second part of the process; viz. when the water raised has passed through the piston valve.

Let the piston be at V, and the level of the water at H″; the downward pressure sustained by the piston, in this case, is evidently the weight of the incumbent water BH″, together with the weight

of the atmosphere. Let h be the number of feet in the height BH″, and $34+h$ will express the number of feet in a column of water, whose base is equal to the section of the piston, and whose weight is equal to the whole downward pressure sustained by the piston.

On the other hand, the upward pressure is produced by the weight of the atmosphere pressing on the water in the reservoir, and transmitted through the column CB, to the lower surface of the piston. But as this pressure has to support the column BC, we must subtract from it the weight of this column, in order to obtain the effective upward pressure on the piston. From a column of water thirty four feet in height, and with a base equal to the section of the piston, subtract as many feet as there are in BC, and we shall obtain a column whose weight is equal to the upward pressure.

The downward pressure equals $34+h$
The upward do. do. $34-\mathrm{BC}$

Remainder $h+\mathrm{BC}$

But $h+\mathrm{BC}=\mathrm{H''B}+\mathrm{BC}=\mathrm{H''C}$.

Thus it appears, that the force necessary to lift the piston, is the weight of a column of water, whose height is that of the column above the level of the water in the well, and whose base is equal to the section of the piston. This force, therefore, from the commencement of the process, continually increases, until the level of the water rises to the discharging spout, and thenceforward remains uniform.*

578. From the foregoing remarks, it is evident that the same force is expended in raising water by means of the pressure of the atmosphere, as when the force is applied directly. We lift upon the atmosphere, instead of lifting directly upon the column of water. This method of raising water from a well, is frequently more convenient than by a simple bucket, but the expenditure of force is the same in both cases.

To compute the actual force necessary to work a pump, (exclusive of the pump rods,) let the height of a discharging spout S, above the level of the water in the well, be expressed in feet, and let the number which expresses it be h. Let the diameter of the piston, expressed in parts of a foot, be d; then the section of the piston ex-

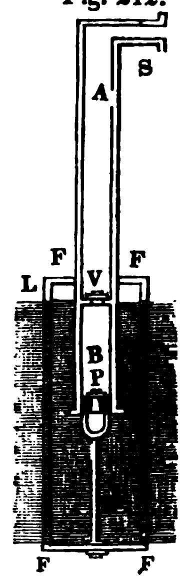
* Library of Useful Knowledge, Art. "Pneumatics."

pressed in parts of a square foot, will be $d^2 \times .7854$. If this product be multiplied by the number of feet h in the height, we shall obtain the number of cubic feet of water which it is necessary to lift at each stroke, since this number $=d^2 \times .7854 \times h$. Now each cubic foot of water weighs about $62\frac{1}{2}$ pounds; hence $d^2 \times .7854 \times h \times 62\frac{1}{2}=$ number of pounds required at each stroke to lift the piston.

The column of water discharged at each stroke, is equal to a column of water, whose base is the section of the piston, and whose altitude is the length of the stroke. The quantity may therefore be found, in cubic feet, by multiplying $d^2 \times .7854$ by the number of feet in the length of the stroke. The weight of the water discharged may be ascertained in pounds avoirdupois, by multiplying this product by $62\frac{1}{2}$.

579. The Lifting Pump.—This pump also consists of a hollow cylinder AB, (Fig. 212.) immersed in the reservoir from which the water is to be raised. A valve opening upwards, is fixed in this cylinder at V, a little below the level L of the water in the reservoir. A piston P, having also a valve opening upwards, is moved in this cylinder by a frame FFFF, connected with the end of the piston rod PH. At the top of the cylinder is a spout S, to discharge the water elevated. Let us suppose the piston P at the bottom B of the cylinder. The pressure of the water in the reservoir, will force water through the piston-valve, until the water rises in the cylinder to the valve V, or to about the level of the water in the reservoir. It would rise to the exact level, but for the weights of the valves. Upon elevating the piston P, the water, not being permitted to pass through the piston-valve, will be pressed against the valve V, and opening it, will pass into the upper chamber VA of the cylinder; from whence it is not allowed to return, since the valve V opens upwards. As the piston rises in BV, the pressure of the water in the reservoir forces water after it into the cylinder; and upon its descent, this water passes through the piston-valve. The next ascent forces water again through V; and so on. The water thus continually forced through V, at

Fig. 212.



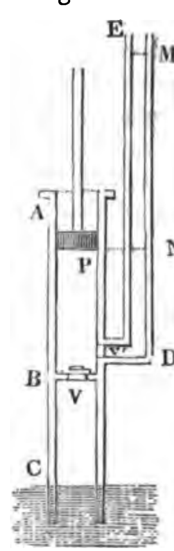
every ascent of the piston, accumulates in the cylinder above the valve V, and its height increases until it reaches the spout S, where it is discharged. This machine may be described in general terms, as follows.

In the Lifting-Pump there is no suction tube, but the exhausting tube, with its piston, is immersed in the reservoir, and on raising the piston, the water is lifted up through a valve at the top of the exhausting pipe, into the ascending pipe.

To find the force necessary to raise the piston, we are to consider that the water in the reservoir balances the water in the cylinder from the bottom B to the level L. The piston, therefore, has only to lift the column from L, to the level of the water in the cylinder. After a few strokes, this water rises to S, and continues permanently at that level afterwards. If, then, the number of feet in SL be called h, and the diameter of the section of the piston, expressed in parts of a foot, be called d, the number of cubic feet of water which presses on the piston, will be expressed by $d^2.7854 \times h$. This product multiplied by $62\frac{1}{2}$, will express the pressure on the piston in pounds; and if to this the weight of the piston and rod, together with the effects of friction, be added, the whole force necessary to lift the piston will be obtained. The quantity of water discharged is found in the same manner as for the suction-pump.

580. The Forcing Pump.—A cylinder ABC (fig. 213.) is placed with its lower end C in the reservoir. It has a fixed valve at V, opening upwards, and a solid piston without a valve, playing air tight in the upper barrel AB. It is connected with another barrel DE by a valve V′ opening upwards and outwards. The tube DE is carried to whatever height it may be necessary to elevate the water. Let us suppose that the solid piston P is in contact with the valve V, and that the water in the lower barrel is at the same level C with the water in the reservoir. Upon raising the piston, the air in BC will be rarefied, and the water will ascend in BC exactly as in the suction-pump. Upon again depressing the piston, the air in PV will be depressed, and it will force open the valve V′, and escape through it. The process, therefore, until water is raised through V into the upper

Fig. 213.



barrel, is precisely the same as for the suction pump, the valve V′ taking the place of the piston-valve in that machine. Now, let us suppose that water has been elevated through V, and that the space PV is filled with it. Upon depressing the piston, this water, not being permitted to return through V, is forced through V′, and ascends in the tube DE. By continuing the process, water will accumulate in the tube DE, until it acquires the necessary elevation, and is discharged. Or, to enunciate the principle of this machine in general terms—

In the forcing pump, the piston has no valve, but the water being elevated into the exhausting tube, as in the suction pump, it is then forced, by the descent of the piston, into the ascending pipe through a valve placed in the side and at the bottom of the exhausting tube.

581. The force requisite to elevate the piston in this pump until the water reaches it, is computed in exactly the same manner as for the suction-pump, and, exclusive of the weight of the piston and its rods, and the effects of friction, it is equal to the weight of a column of water whose base is the section of the piston, and whose height is the distance of the level of the water in the barrel AC, above the level in the reservoir. It is evident also from what has been said on the suction-pump, that the valve V should be less than thirty four feet above the level of the water in the reservoir. If P express in pounds *av.* the weight of the piston and its rods, d be the diameter of a section of the piston expressed in parts of a foot, and h be the number of feet in AC, the force in pounds necessary to lift the piston will be $h \times d^2 \times .7854 + P$.

Let us now examine the force necessary to depress the piston. Let the level of the water in ED be M. The atmospheric pressure on M will be balanced by the same pressure on the piston, by the power of transmitting pressure peculiar to fluids. This force may therefore be neglected; also the part PV′ will balance the part ND of the ascending column, (Art. 456.) Hence it appears, that the pressure exerted by the water in PV on the lower surface of the piston is equal to the weight of a column of water whose base is equal to the section of the piston, and whose height is MN. This, therefore, is the force to be overcome in the descent of the piston, and the

weight P of the piston and its rods assist in overcoming it. Let h' be the number of feet in MN, and the mechanical force necessary to be applied to depress the piston will be expressed in pounds by $h' \times d^2 \times .7854 \times 62.5 - P$.

From these observations, it appears that the weight of the piston and its rods assist the *forcing power* of the machine, but oppose its *suction power*. These effects, therefore, on the whole, neutralize one another.*

582. The entire force used in raising the water, will be found by adding the force necessary to elevate the piston to that which is necessary to depress it. As in this case the weight of the piston and rods increases the one as much as it diminishes the other, the entire force will be the weight of a column of water whose base is the section of the piston, and whose height is PC+MN, that is, the height of the level of the water in the ascending pipe above the level of the water in the reservoir; and expressed in pounds, this is $(h+h') \times .7854d^2 \times 62.5$.

It appears, therefore, that, other circumstances being the same, the power of the forcing-pump has the advantage over that of the suction-pump, by the weight of the piston and its rods.

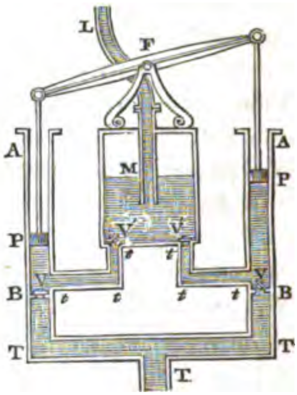
583. In forcing-pumps, since the power is applied by separate impulses, the water would issue in jets were not some contrivance adopted to equalize its flow from the tube. This purpose is effected by means of an air vessel, in which a portion of condensed air is made the medium of communication. The force imparted by successive blows of the piston is first received by this confined body of air, and this, by its elasticity, reacts on the surface of the water in the air vessel, and forces it out by the conducting pipe or hose.

An example of this is afforded in the *Fire Engine*. The fire engine consists of two forcing pumps, which throw the water into an air vessel, from which it is thrown out of the conducting hose by the elastic pressure of condensed air. Thus, (Fig. 214,)

* Library of Useful Knowledge.

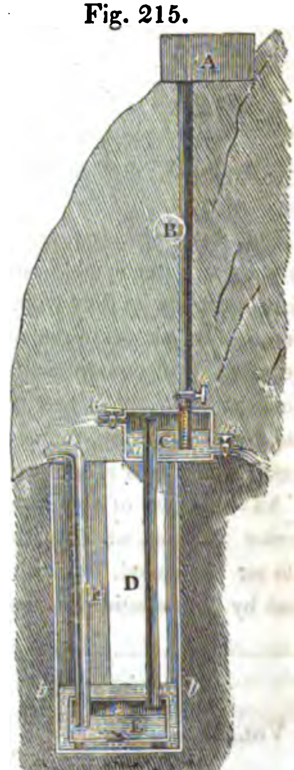
AB, AB are two forcing-pumps, whose pistons PP are wrought by a beam whose fulcrum is at F; VV are valves which open upwards from a suction-tube T, which communicates with a reservoir; *t t* are force-pipes, which communicate by valves V′V′, opening into an air vessel M. A tube L is inserted in the top of this vessel, terminating in a leathern tube or hose, through which the water is forced by the pressure of the air confined in M, which, in consequence of its elasticity, acts nearly uniformly on the surface of the water, and forces it through the hose in a continual stream.

Fig. 214.



584. THE HUNGARIAN MACHINE.—This celebrated machine is employed in draining a mine at Chemnitz, in Hungary. We introduce a description of it here, on account of its affording a good illustration of several hydraulic and pneumatic principles. Here the object is to raise water from a deep mine to the height of ninety six feet, where it can be poured off by a horizontal channel. Now it is easy, in such a case, to take a stream of water near the top of the pit, (and a very small stream will answer the purpose,) and to convey it into a pipe which shall descend into the mine, and afford, by hydrostatic pressure, any degree of force required to raise the water of the mine, not indeed to the top of the pit, for that is hardly ever necessary, but to such a height that it may be poured off by a horizontal drain. In the mine of Hun-

Fig. 215.



gary, the water, which is to supply the required pressure, is taken at the height of two hundred and sixty feet above the surface of the water in the pit. From the cistern A, where the head of water collects, it descends into the perpendicular pipe B, (Fig. 215,) nearly to the bottom of the air-vessel C. Flowing into this, it condenses the air before it, which, by its elasticity, receives and exerts the whole force created by the pressure of the column of water B. This force is transmitted through the air-pipe D, to the surface of the water contained in the well E, which is sunk into the water of the mine, admitting it freely by means of a valve in the bottom opening upwards. This well and the air vessel C, are made strong and air-tight. From near the bottom of the well proceeds a perpendicular tube F, reaching to the height of the drain.

585. We may now easily understand the operation of the machine. We have to raise water ninety six feet, and we can command a column of water two hundred and sixty feet high; but we have no occasion to employ the whole of this force, and so long a column of water would require a pipe of very great strength, especially in the lower parts of it. A column one hundred and thirty six feet long, is found by calculation competent to raise the water in the pit to the required height of ninety six feet, and to make it flow off with a considerable velocity into the drain. Therefore, at the distance of one hundred and thirty six feet from the reservoir, we interpose an air-vessel C, and receive the entire force of the column B upon the air of this vessel, which is compressed into a small space in the upper part of the vessel, and has its elasticity proportionally augmented, (Art. 546.) This force, by means of the pipe D, is transmitted to the surface of the water in the well, and forces the water up the pipe F, which delivers it into the drain. The *principle* of the Hungarian machine, therefore, may be thus enunciated.

*Water is raised by the pressure of a column of water, longer than the column required to be raised, and at a higher level; the pressure being transmitted from one column to the other, through the medium of condensed air.**

* A remarkable fact is mentioned in connexion with the Hungarian Machine, which shows very strikingly, the increase of capacity for

586. **Steam Engine.**—It belongs to Chemistry to investigate the properties of steam, and to Natural Philosophy to apply it as a mechanical agent. The steam engine is the fruit of the highest efforts of both these sciences, and the most valuable present ever made by philosophy to the arts.* As it is impossible clearly to understand the principles and construction of this engine, without a knowledge of the properties of steam, on which they depend, we subjoin an account of a few of its leading properties, referring to chemical authors† for a more detailed view of this subject.

(1.)‡ The great and peculiar property of steam, on which its mechanical agencies depend, is *its power of creating at one moment a high degree of elastic force, and losing it instantaneously the next moment.* This force, acting on the bottom of the piston which moves in the main cylinder, raises it, and fills the space below it with steam. The steam is suddenly condensed, and hence no obstacle is opposed to the descent of the piston, but it is readily forced down again by steam acting from above. This alternate motion of the piston, the rod of which is connected with the working beam, is all that is required in order to communicate motion to all parts of the engine.

(2.) *The elastic force of steam depends on its temperature and density conjointly; and the temperature necessary to its production depends upon the pressure incumbent upon the water during its formation.*

The reason why water boils at the temperature of 212° is, that at that temperature, the vapor acquires just elasticity sufficient to over-

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heat and consequent production of cold, which arises from a sudden enlargement of volume. When the efflux of the water from the pipe F has ceased, if the cock of the air vessel C be opened, the water and air rush out together with prodigious violence, and the drops of water are changed into hail or lumps of ice. It is a sight usually shown to strangers, who are desired to hold their hats to receive the blasts of air; the ice comes out with such violence as frequently to pierce the hat like a bullet.—*Gregory's Mechanics, II.* 221.

* Dr. Black.

† See, especially, Silliman's Chemistry, Vol. I.

‡ See Review of Renwick on the Steam engine, American Journal, XX. 326.

come the atmospheric pressure. Hence, steam produced at the temperature of boiling water, has a force equal to the pressure of the atmosphere. When formed at a lower temperature its elasticity diminishes in a geometrical ratio, and increases in the same ratio when it is formed at a higher temperature. Water boils, or is converted into vapor, at a temperature less than 212°, on high mountains, (Art. 551.) or under the receiver of an air pump, or in other situations where the pressure of the atmosphere is diminished; and in a *vacuum* the boiling point of water is as low as 72°.

(3.) *Heat rapidly augments the elasticity of steam by increasing its density.* If we introduce a few grains of water into a flask, and place it over the fire, the water will soon be converted into steam, which will expel the air of the vessel and fill its whole capacity. If we now close the orifice of the flask and continue the heat, the steam will increase in elastic force in the same manner as air would do under similar circumstances, which is at a comparatively moderate rate, so that it might be heated *red hot* without exerting any very violent force. If, however, the vessel is partly filled with water, and the heat is continued as before, then the elastic force is rapidly augmented, and becomes at length so great as to burst almost any vessel that can be provided; for every new portion of vapor that is raised from the surface of the water, adds to the density of that which was before in the vessel, and proportionally increases its elasticity. In the experiments of Mr. Perkins, a confined portion of steam, not in contact with water, was heated to the temperature of 1400°, and still its pressure did not exceed that of five atmospheres; but, by injecting more water, although the temperature was lessened, the elastic force was gradually increased to one hundred atmospheres.*

(4.) *The space into which a given quantity of water is expanded in becoming steam, depends upon the temperature, and of course upon the degree of pressure, at which it is formed.* Water converted into steam at the temperature of 212°, expands nearly one thousand and seven hundred† times; but at the temperature of 419°, it expands but thirty seven times. According to Dr. Thompson,‡ at a tempe-

* Renwick on the Steam Engine, p. 95.

† It will assist the memory to consider a cubic inch of water as forming a cubic foot of steam, as is nearly the fact.

‡ Outline of the sciences of Heat and Electricity, p. 222.

rature not much higher than 500°, steam would not much exceed double the bulk of the water from which it is generated. The expansive force of such steam would be truly formidable. It would, when it issued into the atmosphere, suddenly expand six hundred and fifty times. We do not know at what temperature water would become vapor without any increase of volume, but we can estimate that it would then support a column of mercury three thousand two hundred and forty three feet (or more than half a mile) high, and would exert a pressure of nearly *twenty thousand pounds* on every square inch.

(5.) *The absolute quantity of heat is always the same in the same weight of steam, whatever may be the temperature of that steam.* When vapor is formed at a low temperature, nearly all the heat that enters it is in the latent state; but as we heat it to a higher degree, its proportion of sensible heat is constantly augmented, and that of latent heat diminished in the same ratio, so that the sum of the two is the same constant quantity.

These preliminary principles being well understood, and kept clearly in mind, it will be easy for the learner to comprehend the principles involved in the steam engine, and the dangers with which it is environed. The general interest felt in this subject renders it one peculiarly deserving of the attention of the student, and induces us to devote a considerable space to the consideration of it.

587. The steam engine owes its present form and perfection, chiefly to the genius and labors of the late *James Watt, Esq.*, of England. His inquires on the subject commenced in the year 1763. The engine in use previous to that time, was what is now called the *atmospheric engine*. It has already been remarked, (Art. 586.) that the chief object in the use of steam is to cause the alternate ascent and descent of a piston moving in a cylinder, since this motion may, by the aid of machinery, be so modified as to answer all the purposes required of the engine. In the atmospheric engine, at the commencement of the operation, the piston remained drawn up to the top of the cylinder, being kept there by the preponderancy of the opposite arm of the lever, or working beam, to which it was attached. Steam being admitted through a valve into the cylinder, expelled the air and occupied its place. Cold water now being admitted, the

steam was suddenly condensed, a vacuum formed, and the atmospheric pressure on the upper side of the piston, having nothing to counterbalance it on the lower side, forced it down to the bottom of the cylinder. Steam being again admitted below the piston, supplied an upward force equivalent to the downward pressure of the atmosphere on the piston, and the preponderancy of the opposite arm of the lever dragged up the piston as before.

It is impossible to understand the reason of the construction of the different parts of Watt's steam engine, without a knowledge of the imperfections of the atmospheric engine, imperfections for which he sought and found a complete remedy. We, therefore, subjoin a brief notice of the successive steps by which Mr. Watt was led to his great improvements.*

588. Mr. Watt was, when a young man, mathematical instrument maker to the University of Glasgow. Being employed to repair a model of an atmospheric engine, belonging to the University, he found the consumption of steam in working this model so great, that he concluded that the quantity wasted must have borne a very large proportion to that expended in working the piston. The reason of this waste will be easily understood. When the steam fills the cylinder, so as to balance the atmospheric pressure on the piston, the cylinder must have the same temperature as the steam itself. Now, on introducing the condensing jet, the steam mixed with this water, forms a mass of hot water in the bottom of the cylinder. This water, not being under the atmospheric pressure, boils at very low temperature, (Art. 586.) and produces a vapor which resists the descent of the piston. The heat of the cylinder itself assists this process; so that, in order to produce a tolerably perfect vacuum under the piston, it was found necessary to introduce so considerable a quantity of condensing water, as would reduce the temperature of the water in the cylinder lower than 100°, and which would consequently cool the cylinder itself to that temperature. Under these circumstances, the descent of the piston was found to suffer very little resistance from any vapor within the cylinder; but then on the subsequent ascent of

* Abridged from Lardner's Lectures on the Steam Engine.

the piston, an immense waste of steam ensued. For on being admitted under the piston, the cold cylinder and water of condensation immediately condensed the steam, and continued to do so, until the cylinder became heated again up to 212°, to which point the whole cylinder must be again heated, before the steam would acquire sufficient elasticity to raise the piston. Here then was an obvious and an extensive source of the waste of heat. At every descent of the piston, the cylinder must be cooled to below 100°; and at every ascent, it must be again heated to 212°. It, therefore, became a question, whether the force gained by the increased perfection of the vacuum, was adequate to the waste of fuel in producing the vacuum; and it was found, on the whole, more profitable not to cool the cylinder to so low a temperature, and consequently to work with a very imperfect vacuum, and a diminished power. Watt, therefore, found the atmospheric engine in this dilemma: either much or little water of condensation must be used. If much were used, the vacuum would be perfect; but then the cylinder would be cooled, and would occasion an extensive waste of fuel in heating it. If little were used, a vapor would remain, which would resist the descent of the piston, and rob the atmosphere of part of its power. The great problem then pressed itself on his attention, *to condense the steam without cooling the cylinder*. To the solution of this problem, Watt now gave his whole mind. The idea occurred to him of providing a vessel separate from the cylinder, in which a constant vacuum might be kept up. If a communication could be opened between the cylinder and this vessel, the steam by its expansive property, would rush from the cylinder to this vessel, where, being exposed to cold, it would be immediately condensed, the cylinder meanwhile being sustained at the temperature of 212°. This happy conception formed the first step of that brilliant career, which has immortalized the name of Watt, and spread his fame throughout the civilized world. He states that the moment the notion of "separate condensation" struck him, all the other details of his improved engine followed in rapid and immediate succession; so that, in the course of a day, his invention was so complete, that he proceeded to submit it to experiment.

589. His first notion was, as has been stated, to provide a separate vessel, called a *condenser*, having a pipe or tube communicating with

the cylinder. This condenser he proposed to keep cold by immersing it in a cistern of cold water, and by providing a jet of cold water to play within it. When the communication with the cylinder is opened, the steam, rushing into the condenser, is immediately condensed by the jet and the cold surface. But here a difficulty presented itself, viz. how to dispose of the condensing water and condensed steam, which would collect in the bottom of the condenser. Besides this, a certain quantity of air would inevitably enter, mixed with the condensing water, which, accumulating, would collect in the cylinder, and resist the descent of the piston. To remedy this, he proposed *to form a communication between the bottom of the condenser and a pump, which he called the* AIR PUMP; *so that the water, the air, and the other fluids, which might be collected in the condenser, would thus be drawn off; and this pump could be worked by the machine itself.*

590. Another inconvenience was still to be removed. On the descent of the piston, the *air* which entered the cylinder from above would lower its temperature; so that, upon the next ascent, some of the steam which entered it would be condensed, and hence would arise a source of waste. To remove this difficulty, Watt proposed to close the top of the cylinder altogether, by an air-tight and steam-tight cover, allowing the piston-rod to play through a hole furnished with a stuffing box, and *to press down the piston by steam instead of the atmosphere.* Watt's grand inprovements in the steam engine, consisted therefore, of three separate steps. The first was the introduction of the *condenser;* the second, the contrivance of the *air pump;* and the third, the employment of *steam* instead of atmospheric pressure, to force down the piston. This third step totally changed the character of the machine. It now became really a *steam engine* in every sense; for the pressure above the piston was the elastic force of steam, and the vacuum below it was produced by the condensation of steam; so that steam was used both directly and indirectly as a moving power; whereas, in the atmospheric engine, the indirect force of steam only was used, being adopted merely as an easy method of producing a vacuum.

591. The last difficulty respecting the economy of heat that remained to be removed, arose from the liability of the external surface of the cylinder to become cool by the circulation of the cold air around it. To obviate this difficulty, Mr. Watt first proposed casing the cylinder in wood, as being a substance which conducted heat slowly. He subsequently, however, adopted a different method, and enclosed one cylinder within another, leaving a space between them, which he kept constantly supplied with steam. Thus the inner cylinder was kept constantly up to the temperature of the steam which surrounded it. The outer cylinder is called the *jacket*.

Watt computed that in the atmospheric engine, three times as much heat was wasted in heating the cylinder, and the other parts of the machine, as was spent in useful effect. And, since in the improvements proposed by him nearly all the waste was removed, he contemplated, and afterwards actually effected, a saving of *three fourths* of the fuel.

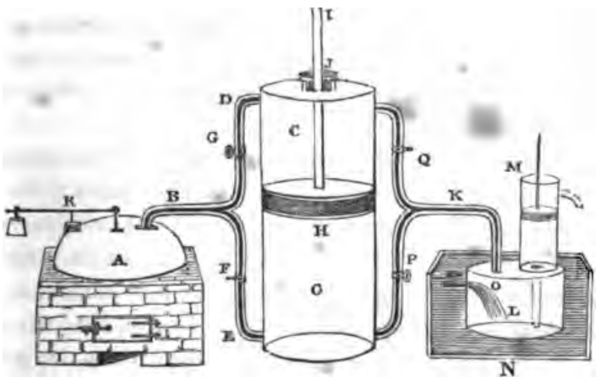
With these things distinctly in view, the learner will now be prepared to understand the construction of this noble engine, in its most improved state.

592. The difficulty of understanding the construction and principles of the steam engine, (as is the case also with many other machines where the parts are numerous,) is greatly enhanced, by the variety of accidental trappings or appendages that are employed about the machine, to perform subordinate offices. As these render the comprehension of the leading principles difficult, when the explanation is attempted from the engine itself, so these inferior parts are often so multiplied in diagrams as greatly to obscure the representation. We shall begin our explanation with a diagram which presents the naked principles divested of all unnecessary appendages.

593. The chief parts of the engine are the *boiler* A, the *cylinder* C, the *condenser* L, and the *air-pump* M. B is the *steam-pipe*, branching into two arms communicating respectively with the top and bottom of the cylinder; and K is the *eduction-pipe*, formed of the two branches which proceed from the top and bottom of the cylinder, and communicate between the cylinder and the condenser. N is a cistern or well of cold water in which the condenser is immersed. Each

branch of pipe has its own valve, as F, G, P, Q, which may be opened or closed as the occasion requires.

Fig. 216.*



594. Suppose, first, that all the valves are open, while steam is issuing freely from the boiler. It is easy to see that the steam would circulate freely through all parts of the machine, expelling the air, which would escape through the valve in the piston of the air-pump, and thus the interior spaces would be all filled with steam. This process is called *blowing through:* it is heard when a steam-boat is about setting off. Next, the valves F and Q are closed, G and P remaining open. The steam now pressing on the cylinder forces it down, and the instant when it begins to descend, the stop cock O is opened, admitting cold water which meets the steam as it rushes from the cylinder and effectually condenses it, leaving no force below the piston to oppose its descent. Lastly, G and P being closed, F and Q are opened, the steam flows in below the piston and rushes from above it into the condenser, by which means the piston is forced up again with the same power as that with which it descended. Meanwhile the air-pump is playing, and removing the water and air from the condenser, and pouring the water into a reservoir, whence it is conveyed to the boiler to renew the same circuit.

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* From Jones' Conversations on Chemistry, a work which contains a very luminous view of the elementary principles of the steam engine

595. The kind of valve chiefly employed in the steam engine is that called the *puppet valve.** It resembles the stopper of a decanter, but is more obtuse. All these various appendages of the machine, are carried by the engine itself; the air pump is worked by having its piston rod attached to one arm of the working beam, and the valves are opened at the instant required by means of levers, to which motion is communicated from the same source.

596. Soon after the invention of these engines, Watt found that, in some instances, inconvenience arose from the too rapid motion of the steam piston at the end of its stroke, owing to its being moved with an *accelerated motion.*† This was owing to the uniform action of the steam pressure upon it. For on first putting it in motion, at the top of the cylinder, the motion was comparatively slow, but from the continuance of the same pressure the velocity with which the piston descended was continually increasing, until it reached the bottom of the cylinder, when it acquired its greatest velocity. To prevent this, and to render the descent as nearly uniform as possible, it was proposed to cut off the steam before the descent was completed, so that the remainder might be effected merely by the expansion of the steam which was admitted to the cylinder.‡ To accomplish this he contrived, by means of a pin on the rod of the air-pump, to close the upper steam-valve when the steam-piston had completed one third of its entire descent, and to keep it closed during the remainder of that descent, and until the piston again reached the top of the cylinder. By this arrangement, the steam pressed the piston with its full force through one third of the descent, and thus put it into motion; during the other two thirds of the way, the steam thus admitted acted merely by its expansive force, which became less in exactly the same proportion as the space, given to it by the descent of the piston, increased. Thus during the last two thirds of the descent, the piston is urged by a gradually decreasing force, which in practice is found

* Seen at V, fig. 165, Vol. I. p. 271.

† For since the steam *continues* to act upon the piston during its descent, its velocity would be constantly increased, like that of a ball in the barrel of a gun. (Art. 334.)

‡ Steam engines constructed on this principle are said *to act expansively.*

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just sufficient to keep up in the piston a uniform velocity. Another advantage gained by this contrivance independently of the uniformity of motion was, that two thirds of the fuel was saved; for instead of consuming a cylinder full of steam each descent of the piston, only one third of a cylinder full was necessary.

597. From the foregoing account of the principles of the steam engine, the learner will be able to give a full explanation of the construction and use of the various parts of this important and interesting machine,* from the figure.

A. The Boiler.
B. The Steam Pipe, conveying the steam to the cylinder, having a steam-cock *b* to admit or exclude the steam at pleasure.
C. The Cylinder, surrounded with the *jacket c c*.
D. The Eduction Pipe, communicating between the cylinder and the condenser.
E. The Condenser, with a valve *e*, called the *Injection-cock*, admitting a jet of cold water, which meets the steam the instant the latter enters the condenser.
F. The Air Pump.
G.G. Cold Water Cistern, for the Condenser, filled by
H. The Cold Water Pump.
I. The Hot Well, containing water from the condenser.
K. The Hot Water Pump, which returns the water of condensation to the boiler.
L.L. Levers, which open and shut the valves in the channel between the Induction Pipe, Cylinder, Eduction Pipe, and Condenser; which levers are raised or depressed by projections attached to the piston rod of the condenser.
M.M. Apparatus for parallel Motion,† (Art. 411 and 12.)
N.N. The Working Beam.
O.O. The Governor. (Art. 396.)
P. The Crank. (Art. 407.)
Q.Q. The Fly Wheel. (Art. 392.)

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* One of the best descriptions of the steam engine may be found in Millington's *Epitome of Natural Philosophy*.

† In the Engines constructed recently at New York, under the direction of Mr. R. L. Stevens, a substitute for the parallel motion has

598. The working beam is here represented as acting immediately upon the fly wheel, from which, as from a reservoir, motion may be distributed to all parts of the engine. (Art. 392.) It is obvious, however, that the same end of the working beam, instead of expending its force upon the fly wheel, may be connected directly with the piston rod of a pump for raising water, or with a horizontal shaft with wheels, as in the steam-boat. In some steam-boats, particularly those of a large size, the fly wheel is dispensed with, the inertia of the boat itself being sufficient to regulate the motion. (Art. 391.)

599. In steam engines of the foregoing construction, the pressure introduced on one side of the piston derives its efficacy, either wholly or in part, from the vacuum produced by condensation on the other side. This always requires a condensing apparatus, and a constant and abundant supply of cold water. An engine of this kind, must therefore necessarily have considerable dimensions and weight, and is inapplicable to uses in which a small and light machine only is admissible. If the condensing apparatus be dispensed with, the piston will always be resisted by a force equal to the atmospheric pressure, and the only part of the steam pressure which will be available as a moving power, is that part by which it exceeds the atmospheric pressure. Hence, in engines which do not work by condensation, steam of a much higher pressure than that of the atmosphere, is indispensably necessary; and such engines are therefore called *High Pressure Engines*. The steam, when it has once produced its effect in raising or depressing the piston, escapes into the atmosphere, not being condensed and returned to the boiler as in low pressure or condensing engines. In these engines the whole of the condensing apparatus, viz. the cold water cistern, condenser, air-pump, &c. are dispensed with, and nothing is retained except the boiler, cylinder,

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been introduced, that performs the task equally well, and is much less complex. On the head of the piston rod a bar is fixed, at right angles to it, and to the longitudinal section of the engine. The ends of this bar work in guides formed of two parallel and vertical bars of iron, by which the upper end of the piston-rod is constrained to move in a straight line. (*Renwick.*)

piston, and valves. Consequently, such an engine is small, light, and cheap. It is portable also, and may be moved, if necessary, along with its load, and is therefore well adapted to locomotive purposes. Hence its use in small steam-boats, and in locomotive carriages or railways.

CHAPTER VI.

OF ACOUSTICS.

600. ACOUSTICS* *is the science which treats of the nature and laws of* SOUND.

Sound and its Modes of Production.†

601. If we rub our moistened finger along the edge of a drinking glass, or draw a bow across the strings of a violin, we can in both cases procure sounds which remain undiminished in intensity, as long as the operation by which they are excited is continued. A similar fact takes place with respect to any other sonorous body, whose structure is not destroyed by the mode of excitation employed.

602. Though all bodies may, by some mode of excitation, be made to sound, there is a great difference among them in the *intensity* of the sounds which they produce during the operation, and in the *permanence* of these sounds after the excitation has ceased. Thus if we strike two bells, one of lead and the other of brass, the sound of the lead is feeble and momentary compared with that of the brass. In the former, therefore, that action by which the body produces sound, is excited only in a small degree, and ceases with the excitement; in the latter there is some power by which, when the action is once begun, it is continued for some time afterwards. By examining the characteristic difference between these two classes of bodies,

* From ακουω, *to hear.*

† This section is taken chiefly from the Edinburgh Encyclopædia, Art. *Acoustics.*

we may be enabled to discover what are the physical properties on which the production of sound depends, and what is their mode of action. This difference is found to depend on the *substance* and *form* of the sounding bodies, and also upon the various external circumstances in which they are placed.

603. In comparing the properties of these substances, we shall find them distinguished from each other by the degree of *vibration* which they are capable of receiving, and by the *length of time* during which they can preserve a *vibratory motion;* those substances which are most capable of vibration being most sonorous, and those which can longest maintain a state of vibration, also persevering longest in emitting sound. Bodies, though of the same substance, differ in these respects according as their form varies; those forms which are most favorable to the production and continuance of a vibratory motion, being also most favorable to the production and permanence of sound. Thus, a hollow globe of brass is far less sonorous than the hemispheres which are made by dividing it into two equal parts, since the structure of a globe is such that the parts mutually support each other, like a continued arch, while the form of the hemispheres, which approaches that of a bell, is peculiarly liable to a tremulous vibratory motion.* Indeed, when a body sounds powerfully, as a large bell, or the lowest string of a harpsichord, we can perceive that it actually vibrates; and even in cases where the vibration is imperceptible to the naked eye, we may detect it by the microscope, or by some other artifice. Thus, if we put some water into a glass tumbler or basin and make it sound, by applying the moistened finger, as in Art. 601, the water will be agitated. If we hold the hand over the pipe of an organ, we shall feel a tremulous motion in the air passing through it. Such experiments may be extended to all solid bodies by placing upon them pieces of paper, or strewing them with fine sand. Hence,

Vibrations, in the sounding body, are the immediate cause of sound.

604. Whatever may be the remoter cause of sound, vibrations must be considered as the *immediate* cause, since they always pre-

* Millington's Natural Philosophy, p. 123.

cede or accompany it, and since whatever affects the vibration of a body, produces a corresponding effect upon the qualities of the sounds which it emits, while those bodies whose sounds are similar, have something in common in their mode of vibration.

605. All continued sounds, which remain in any degree uniform throughout their duration, are capable of being compared with each other in their degree of acuteness. *When sounds are equally acute, they are said to have the same pitch;* but when they differ in acuteness, that sound which is more shrill is said to be acute, or to have a higher pitch; and that which is less shrill, is said to be *grave*, and to have a lower pitch, or a deeper tone. A difference in pitch forms the chief character by which *musical sounds* are distinguished from each other, and is the foundation of their use in music. In unmusical sounds, it generally holds a place subordinate to their other qualities.

Musical sounds have occupied the attention of philosophers more than any other class of sounds. The superior precision with which the ear can estimate any variation in pitch, renders these sounds more easily compared; and the vibration of the sonorous bodies which produce them, are, on account of their superior simplicity of form, more easily investigated.*

606. Musical strings.—A musical string is of a uniform thickness, and is stretched between two points, by a force much greater than its weight. The stretching force is generally conceived as measured by the weight, which would occasion an equal tension, on the supposition that the string is made fast at one end and passes over a pulley at the other, the latter being loaded with weights. In the usual mode of exciting a musical string, it vibrates on each side of its quiescent position, the extremities being the only points which remain at rest. The sound which the string gives in this mode of vibration is called its *fundamental* sound.

607. The pitch of the fundamental sound of musical strings, is found by experience to depend on three circumstances; the *length* of

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* Ed. Encyc. Art. *Acoustics.*

the string,—its *weight*, or quantity of matter,—and its *tension*. The tone becomes more acute as we increase the tension, or diminish either the length or the weight. The operation of these several circumstances may be seen in a common violin. The pitch of any one of the strings is raised or lowered by turning the screw so as to increase or lessen its tension; or, the tension remaining the same, higher or lower notes are produced by the same string, by applying the fingers in such a manner as to shorten or lengthen the string which is vibrating; or, both the tension and the length of the string remaining the same, the pitch is altered by making the string larger or smaller and thus increasing or diminishing its weight.

608. The time of a *double vibration*, is the time occupied by a string in passing from a point to which it is stretched on one side to the opposite extreme, and returning to the same point again. It has been demonstrated, that the time of a double vibration, expressed in parts of a second of time, will be found by the following operation:

Multiply the number of inches described by a falling body in a second of time, by the weight which is equal to the force of tension; and by this product divide the weight of two inches of the string, extract the square root of the quotient, and multiply the root thus found by the length of the string in inches; the result will be the time of a double vibration expressed in parts of a second of time. Or, algebraically thus:—Let L represent the length of the string in inches; w, the weight of an inch of the string; t, a weight equivalent to the force of tension; g, the rate of a falling body $=193$; and T the time of a double vibration expressed in seconds. Then

$$T=L\sqrt{\frac{2w}{gt}}=L\sqrt{\frac{2w}{193t}}.$$

609. As the distance of the string from its quiescent position, does not form an element of the algebraic expression, which is thus found for the time of a vibration, it follows that this time is independent of the distance. Hence, as in the pendulum,

The vibrations of a string, fixed at both ends, are performed in equal times, whether the length of the vibrations be greater, or smaller.

610. Upon this uniformity in the times of vibration depends the *uniformity of tone;* for if we employ a string of unequal thickness, and consequently one whose vibrations are performed in different times, the sound is confused and variable, and any other mode by which we destroy the isochronism, produces a similar effect. The same law has been found to extend to all other cases of musical sounds; and, therefore, we may conclude, that *isochronism in the vibrations of sonorous bodies, is essential to their producing musical sounds.*

611. The number of vibrations performed by a string in a second of time, being inversely as the time of one vibration, it is expressed by the reciprocal of the formula denoting the time; so that if N represents the number of vibrations, we shall have the following expression: $N = \frac{\sqrt{193t}}{L\sqrt{2w}}$.

The frequency of vibration which this equation gives, is found to agree very exactly with the result of experiments performed with strings, whose vibrations are so slow as to admit of being numbered.

612. The *relation* between the number of vibrations performed by *different strings,* may be expressed by a more simple formula; for g and the number 2 being both constant quantities, they may, in this case, be rejected, and we get the following expression: $N \propto \frac{\sqrt{t}}{L\sqrt{w}}$. According, then, as we diminish the length of a string, and the weight of an inch of it, or increase its tension, we increase its frequency of vibration; but equal changes in these circumstances do not produce equal effects. Thus, if in different strings their tension and the weight of an inch remain the same, *their frequency of vibration will be inversely as their lengths;* for then $N \propto \frac{1}{L}$. If we make the length one third, we triple the number of vibrations, and so for any other proportion. If the length and tension remain the same, $N \propto \frac{1}{\sqrt{w}}$, or *the number of vibrations is inversely as the square roots of the weights:* consequently a string four times as heavy as another

will vibrate half as fast. The bass strings in most instruments, have fine wire twisted round them to increase their quantity of matter, otherwise greater length must be resorted to for the production of similar tones. If the length and the weight of equal portions be the same, then $N \propto \sqrt{t}$, or *the frequency of vibration is as the square root of tension.* Therefore, we must give the string of a violin four times the tension in order to make it vibrate twice as fast.

613. WIND INSTRUMENTS.—In wind instruments, a column of confined air itself is the vibrating body; and here the vibrations are longitudinal instead of lateral, as is the case with strings. That it is really the air which is the sounding body in a flute, organ pipe, or other wind instrument, appears from the fact, that the materials, thickness, or other peculiarities of the pipe, are of no consequence. A pipe of paper and one of lead, glass, or wood, provided the dimensions are the same, produce, under similar circumstances, exactly the same tone as to *pitch*. If the *qualities* of the tones produced by different pipes differ, this is to be attributed to the friction of the air within them, setting, in feeble vibration, their own proper materials.* The class of bodies vibrating *longitudinally*, is not only more diversified in its powers than the other classes of sounding bodies, but also more extensive in the range of substances which it comprehends. A uniform rod under any solid substance, or a column of air contained in a cylindrical tube, whose diameter is every where equal, may have its vibration limited at both extremities by an immovable obstacle; or both extremities may be at liberty; or one extremity may be confined and the other disengaged.

614. A column of air, or a rod of any substance, whether confined or free at both extremities, performs a double vibration in the same time that a minute impulse would occupy, when travelling in a medium of the substance through twice the length of the sonorous body; and a body fixed at one extremity only, will occupy double that time. Hence, the number of vibrations performed in a second of time by a given body, is the same, whether that body be fixed at both extremities, or free at both; and therefore its sound in these

* Herschel.

two cases should be the same. But if the body be fixed at one extremity and free at the other, its length must be reduced to one half, to make it give the same tone as in the two former cases. Thus, if we blow into a tube closed at one extremity, it will give the same tone as we procure by blowing into an open tube of double the length.

615. The different *pitch* of bodies vibrating longitudinally, and free at both extremities, depends on four circumstances, viz. their elasticity, the temporary rate at which their elasticity is increased by condensation, their length, and their specific gravity, the tone of a body being more acute, according as the elasticity, and the rate of its increase by condensation, are greater, or the length and specific gravity less. The *length* of the sonorous body is almost exclusively the only one of these circumstances which we have completely in our power; and with regard to ordinary wind instruments, and all musical instruments where common air is the vibrating body, the length is the circumstance of most importance, since the elasticity, rate of condensation, and specific gravity are then nearly constant quantities. The change of specific gravity, however, to which the air is subject in consequence of changes of temperature, materially affects the pitch of wind instruments. The frequency of vibration of a column of air is found to be increased about $\frac{1}{33}$, by an elevation of 30° Fahrenheit. Thus, the tone of an organ has been found to be higher in summer than in winter; and flutes and other wind instruments become gradually more acute as the included air is heated by the breath.*

616. Bells.—If a bell be struck by a clapper on the inside, the bell is made to vibrate. The base of the bell is a circle; but it has been found that, by striking any part of the circle on the inside, that part flies out, so that the diameter which passes through this part of the base, will be longer than the other diameters. The base is changed by the blow into the figure of an ellipse, whose longer axis passes through the part against which the clapper is thrown. The elasticity of the bell restores the figure of the base, and again elongates the bell in a direction opposite to the former; and the two

* Ed. Encyc. Art. *Acoustics*.

elliptical figures thus alternate with each other, growing smaller and smaller, like the vibrations of a pendulum when the moving force is withdrawn, until the sound dies away. We may be convinced by our senses, that the parts of the bell are in a vibratory motion while it sounds. If we lay the hand gently upon it, we shall feel this tremulous motion, and even be able to stop it; or if small pieces of paper be put upon the bell, its vibrations will set them in motion.*

We may conceive the bell to be formed of an infinitude of rings, placed one above another from the base to the highest point. The rings situated nearer to the base, having a greater circumference, tend to perform their vibrations more slowly, while the rings nearer to the summit, whose circumferences are smaller, tend to produce vibrations oftener. These sounds will so coalesce as to produce a mixed sound, intermediate between those of the higher and lower rings.†

Propagation of Sound.

617. Air is, in general, the medium of sound. A bell struck under the receiver of an air pump, gives a feebler and feebler sound as the exhaustion proceeds, until, when the rarefaction is carried to a certain extent, it emits no sound at all.‡ Hence, on the summit of high mountains, where the air is naturally rare, sound ought to be weaker than at the general level of the earth; and such is found to be the fact. Saussure relates that upon the top of Mount Blanc, the firing of a pistol made a report no louder than that of a child's toy-gun. A fact mentioned by travellers in Alpine countries, is explained on this principle. They see distinctly a huntsman on a neighboring eminence, and observe the flashes of his gun, but can scarcely hear the report, even when comparatively near them.§

Yet meteoric bodies are said to give a distinct rumbling sound in passing through the air at the height of fifty miles, an altitude at which the air is rarefied to a degree exceeding the vacuum of the

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* Haüy's Nat. Phil. I, 203; Partington's Manual I, 257.
† Haüy's Nat. Phil. I, 306.
‡ Herschel in Encyc. Metrop. II, 747.
§ Partington, I, 263.

air pump. Dr. Halley mentions an instance of a meteor, whose elevation was at least sixty nine miles, exploding with a sound equal to "the report of a very great cannon, or broad side." Probably, however, these sounds do not emanate from the meteor itself, but from fragments projected from it, which fall through the air to the ground. If the "rumbling sound" above mentioned, proceeds from the body of the meteor, it is necessary to suppose that the air is condensed before it to a great extent. On the other hand, when the elasticity of the air is augmented, either by condensation or heat, the force of sound is considerably increased. This effect has been experienced in the condensed air of diving bells.

618. But what is the change wrought in the air by sounding bodies? Let us take, for example, a cord of a stringed instrument, and suppose it struck as when played upon; immediately all the points of that string will deviate more or less from the position which they occupied when the string was at rest, according as they are more or less distant from the points where the string is fixed; and the string will go and return alternately on this side, and on that side of its first situation, by a vibratory motion occasioned by its elasticity. The particles of air, contiguous to the different points of the string, assume motions similar to those of the respective points, that is, they move backwards and forwards with them. Each particle communicates motion to that which is next to it, that to a third, and so on, until the particles of air are reached which are in contact with the tympanum, or drum of the ear. The air then acts upon that membrane, by communicating to it its own vibrations, which the drum transmits to the auditory nerve; and thence results the sensation of sound.* The agency of air, therefore, as the medium of sound, may be briefly expressed thus:

Air receives from sounding bodies vibrations, which it communicates to the organs of hearing.

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* Haüy, I, 203.——It is evident from the mechanical concussiôn attending loud noises, that sound consists in a motion of the air itself communicated along it by virtue of its elasticity, as a tremor runs along a stretched rope.—*Herschel on Sound.*

619. In an open space, and in a serene atmosphere, sound is propagated from the sounding body in all directions. Sounds, even the most powerful, when thus transmitted freely through the air, diminish rapidly in force, as they depart from their sources, and within moderate distances wholly die away. What *law* this diminution follows, is not yet ascertained; and is, indeed, in the present state of Acoustics, incapable of determination. Some writers have supposed that sound follows the common law of emanations radiating from a center, (Art. 11.) and, consequently, that its intensity at different distances from its source varies inversely as the square of the distance;* but we can estimate the force of sounds by the ear alone; an instrument of comparison whose decisions on this point vary with the bodily state of the observer, and whose scale expresses no definite relation but that of equality.

620. Though sound has in general, at its origin, a tendency to diffuse itself in all directions, it is sometimes more propagated in one direction than in others. A cannon seems much louder to those who stand immediately before it, than to those who are placed behind it. The same fact is illustrated by the speaking trumpet; the person towards whom the instrument is directed, hears distinctly the words spoken through it, while those who are situated a little to one side, hardly perceive any sound.

621. Sound is in a great measure intercepted by the intervention of any solid obstacle between the hearer and the sonorous body. Thus, if while a bell is sounding, houses intervene between us and the bell, we hear it sound but faintly, compared with what we hear after we have turned the corner of the building. From this fact sound would seem to be propagated in straight lines. If, however, we speak through a tube, the voice will be wholly confined by the tube, and will follow its windings however tortuous; hence we infer that sound is propagated not in right lines like radiant substances as heat and light, but in *undulations*, after the manner of waves, such as follow when a stone is thrown into still water.

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* Millington's N. Phil. p. 125. Epit.—Herschel on Sound, Encyc. Metropol. II. 773.

621. Though air is the most common medium of sound, yet it is not the only medium. Various other bodies, both solid and fluid, are excellent conductors of sound; and the fainter sound of the bell when buildings intervene, as in the case supposed, (Art. 621.) arises from the fact, that *sound passes with difficulty from one medium into another.*

622. If a log of wood is scratched with a pin at one extremity, a person who applies his ear to the other extremity will hear the sound distinctly; and when a long pole of wood is applied at one end to the teeth, the ticking of a watch may be heard at the other end, at a much greater distance, than when there is no medium of communication but the air. The motion of a troop of cavalry is heard at a great distance by applying the ear close to the ground, and it is well known that dogs by this method first discover the approach of a stranger.

623. *The* VELOCITY *of sound is progressive.* Thus when a gun is fired at a distance from us, we perceive the flash some time before we hear the report. Thunder follows the lightning at a perceptible interval, although they are known to be cotemporaneous events. If a gun be fired at a certain known distance, and we observe the interval between the flash and the report, we may obtain the rate at which sound passes, that is, the velocity of sound. Many years since, Dr. Derham made a number of accurate and diversified experiments on this subject, and fixed the velocity of sound at 1142 feet per second. The mean of a great number of experiments give the average velocity of 1130 feet per second; but the velocity as determined by Derham, namely, 1142 feet per second, is that which has been generally admitted as the standard. Since, however, the transmission of sound depends on the elasticity of the medium, (Art. 615.) causes which affect the elasticity, likewise affect the velocity of sound. Thus, the velocity is a little greater in warm than in cold air, and consequently is somewhat influenced by climate.* M. Goldingham, by a series of experiments made at Madras, found that the velocity of sound was affected even by the seasons of the year, in-

* Partington, I, 263.

creasing regularly from the coldest to the hottest months, and afterwards regularly decreasing. Hence, for every degree of Fahrenheit's thermometer 1.14 feet is allowed for the velocity of sound per second. A similar gradation in the velocity of sound at different seasons of the year, was observed by Capt. Parry in his experiments on sound within the frigid zone.*

624. *Sound moves with a uniform velocity;* that is, it passes over equal spaces in equal times. This important fact was first ascertained by Derham, who found that it held good whether the sound were strong or feeble, whether it proceeded from a hammer or a cannon: in short, that neither the strength nor the origin of the sound made any difference. M. Biot caused several airs to be played on a flute at the end of an iron pipe 3120 feet long, and the notes were distinctly heard by him at the other end, without the slightest derangement in the order or quality of the sounds.

625. The velocity of sound, however, when transmitted through the air, is slightly influenced by the strength and direction of the *wind*. Dr. Derham found that when the wind is blowing in the direction of the sound, its velocity must be added to the standard velocity of sound, and must be subtracted from it when opposed to it.† A *transverse* wind does not affect the velocity of sound in the slightest degree.

626. Several distinguished philosophers, both of France and Holland, have recently made experiments on the velocity of sound under circumstances the most favorable to the attainment of accurate results. A difficulty experienced by the earlier experimenters, as Der-

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* Phil. Trans. 1828, p. 97.

† If a stone be thrown into a still lake, the waves spread with equal rapidity in all directions, in circles whose center is the stone. If into a running river, still they form circles, but their center is carried down the stream; and, in point of fact, the wave arrives opposite to the point of the bank *above* the place where the stone fell, later than at a point at the same distance below it in proportion to the rapidity of the stream.—*Herschel on Sound.*

ham, arose from the want of a method of measuring a small fraction of a second, and yet this was necessary where a variation of one hundredth part of a second makes a difference of more than eleven feet in the result. The Dutch experimenters* employed a clock with a conical pendulum, capable of determining intervals to the hundredth of a second, by suddenly suspending the motion of the index without stopping the clock. In the French experiments a kind of watch was used, one of whose hands performed a revolution in a second, and could be made to touch with its extremity the dial plate, at any instant, and leave there a dot, without interrupting its motion of rotation, by the sudden pressure of a small lever; to effect which it carried with it a drop of printer's ink in a peculiar and ingenious species of dotting pen. By the use of these instruments, it was found practicable to ascertain the interval between the sight of a flash, and the arrival of the report of a gun, with such precision as to destroy all material error in the result which might arise from this cause. Accordingly, their results afforded a striking agreement,—the experiments of the French gave for the velocity of sound, per second, 1086.1 feet: those of the Dutch, 1089.42, both considering the air at the temperature of freezing water. But it is found that the velocity is increased 1.14 feet for every degree of Fahrenheit; consequently, reducing the estimate to the temperature of 62½°, (which is the standard temperature of the British metrical system,) the velocity becomes 1124.19, as determined by the Dutch experimenters, which is deemed the most accurate result hitherto obtained. It may, therefore, be stated in round numbers, that sound passes through air at the rate of nine thousand feet in eight seconds, or twelve miles and three fourths per minute, or seven hundred and sixty five miles an hour, which is about three fourths of the diurnal velocity of the earth's equator. Hence, in latitude 42½° if a gun were fired at the moment a star passes the meridian of any station, the sound would reach any other station exactly west of it at the precise instant of the same star's arriving on its meridian; that is, it would keep pace with the velocity of the earth at that place, as it turns on its axis, in the diurnal revolution.†

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* Moll, Vanbeck, &c.

† Herschel on Sound, in Encyc. Metrop. II, 751.

627. From a knowledge of the velocity of sound, the *distance* of a sounding body may be estimated. Thus if the interval between seeing a flash of lightning, and hearing the thunder be six seconds, the distance of the cloud is $6 \times 1142 = 6852$ feet, or $1\frac{3}{10}$ miles.

628. *The air is a better conductor of sound when humid than when dry.* Thus, a bell is heard better just before a rain; and this fact lends some countenance to an opinion of the ancients, that sound is heard better by night than by day. Humboldt was particularly struck with this fact, when he heard the noise of the great cataracts of Orinoco, which he describes as three times greater in the night than in the day.*

629. The *distance* to which sound may be heard, will of course vary with its force and various other circumstances which are incapable of being reduced to an exact law. Volcanoes, in South America, have sometimes been heard at the distance of three hundred miles; and naval engagements have been heard at the distance of two hundred miles. The unassisted human voice has been heard from Old to New Gibraltar, a distance of ten or twelve miles, the watch word *All's Well* given at the fomer place being heard at the latter. Sounds are heard to a much greater distance over water than over land, and farther on smooth than on rough surfaces.

630. *Liquids are good conductors of sound.* Indeed, sound is conveyed with far greater velocity in water than in air, and this too in consequence of its greater elasticity; (Art. 615.) for, since water has been found, by Perkins and others, capable of compression and of restoring itself when the compressing force is removed, it is to be accounted not only elastic, but as exceeding aëriform bodies in elasticity in proportion as the force required to compress it is greater. Dr. Franklin, having plunged his head below water, caused a person to strike two stones together beneath the surface, and heard the sound

* Humboldt, however, accounts for the greater audibility of sounds by night than by day, from the absence of those ascending and descending currents of air which, while the sun is shining, impair the uniformity of the medium, and thus diminish its conducting powers.

distinctly at the distnnce of more than half a mile. By similar experiments, it has been ascertained, that, though water is a much better conductor of sound than air, yet the sound is greatly enfeebled by passing out of one medium into the other. The most accurate experiments on this subject, are those made in the year 1826 by M. Colladon, in the Lake of Geneva. He caused a bell to be rung under water, and found that although the sound of the blow was well heard in the air directly above the bell, yet the intensity of the sound diminished very rapidly as the observer removed from its immediate neighborhood, and at the distance of two or three hundred yards, it could no longer be heard at all.* To conduct the sound from the water to the ear, a tin pipe was employed, which was plunged into the water, and the ear brought close to the upper end. By this contrivance he was enabled to hear the strokes of the bell in water, at the distance of about nine miles. The velocity of sound under water, M. Colladon found to be four thousand seven hundred and eight feet, or nearly a mile, per second.†

631. *Solid substances convey sound with various degrees of facility, but in general much better than air, and as well or even better than fluids.* By placing the ear against a long dry brick wall, and causing a person at a considerable distance to strike it *once* with a hammer, the sound will be heard *twice*, because the wall will convey it with greater rapidity than the air, though each will bring it to the ear.‡ The rate at which *cast iron* conducts sound, was ascertained by M. Biot in the following manner. He availed himself of the laying of a series of iron pipes to convey water to Paris. The pipes were about eight feet in length, and were connected together with small leaden rings. A bell being suspended within the cavity, at one end of the train of pipes, on striking the clapper at the same instant against the side of the bell, and against the inside of the pipe,

* It is inferred from this experiment, that sound is reflected by the same laws as light: when the direction is perpendicular to the reflecting surface, (in this case, the surface of the water,) it passes without reflection; but the quantity reflected increases, as the angle of reflexion is more oblique.

† Herschel.

‡ Millington, p. 125.

two distinct sounds successively were heard by an observer stationed at the other extremity. With a train of iron pipes two thousand five hundred and fifty feet, or nearly half a mile in length, the interval between the two sounds was found from a mean of two hundred trials, to be 1.79 seconds. But the transmission of sound through the internal column of air, would have taken 2.2 seconds; which shows that the sound occupied only .41 of a second in passing through the metal. From more direct trials, it was concluded that the exact interval of time, during which the sound performed its passage through the substance of the train of pipes, amounted to only the .26 of a second, showing that iron conducts sound about ten times as rapidly as air does.*

632. If a string be tied to to a common fire shovel, and the two ends of the string be wound around the fore fingers of each hand, and the fingers be placed in the ears, on striking the bottom of the shovel against an andiron or other solid body, very deep and heavy tones will be heard, and the vibrations of the metal will be clearly perceived.

633. Solids, as well as other bodies, owe their power of conducting sound to their elasticity. By elasticity in a solid, however, is not meant, a power of undergoing *great* extensions and compressions,

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* Herschel observes, that from this determination we may estimate the time it requires to transmit force, (whether by pulling, pushing, or by a blow,) to any distance, by means of iron bars or chains. For every eleven thousand and ninety feet of distance (= the velocity of sound per second in iron,) the pull, push, or blow will reach its point of action, one second after the moment of its first emanation from the first mover. In all moderate distances, then, the interval is utterly insensible. But, were the sun and the earth connected by an iron bar, no less than one thousand and seventy four days, or nearly three years, must elapse before a force applied at the sun could reach the earth. The force actually exerted by their mutual gravity may be proved to require no appreciable time for its transmission. How wonderful is this connexion!—*Herschel on Sound, Encyc. Metrop.* II, 773.

after the manner of air, or India-rubber, and returning readily to its former dimensions; but rather what is commonly called *hardness*, in contra-distinction to toughness, a violent resistance to the displacement of its molecules *inter se* in all directions. Thus the hardest solids are, in general, the most elastic, as glass, steel, and the hard brittle alloys of copper and tin, and in proportion as they are elastic, they are adapted to the free propagation of sound through their substance. But an important condition in their constitution is, that their substance be *homogeneous*, and their structure *uniform*. By the want of homogeneity and uniformity in the conducting medium, the sonorous pulses are every instant changing their medium, and the general wave is broken up into a multitude of non-coincident waves, emanating from different origins, and crossing and interfering with each other in all directions. Thus, a glass vessel contaning an effervescing liquor, cannot be made to ring, but gives a dead sound; but as the effervescence subsides, the tone becomes clearer, and when the liquid is perfectly tranquil, the glass rings as usual.*

634. The great power of solid bodies to conduct sound is exemplified in *earthquakes*, which are heard almost simultaneously in very distant parts of the earth. *Musical boxes* sound much louder when placed on a table or some solid support, than when the air affords the only conducting medium. It is easy to ascertain whether a kettle boils, by putting one end of a stick or poker on the lid, and the other end to the ear: the bubbling of the water, when it boils, appears louder than the rattling of a carriage in the streets. A slight blow given to the poker, of which the end is held to the ear, produces a sound which is even painfully loud.†

635. A physician of Paris introduced into medical practice an instrument, depending on the power of solid bodies to conduct sound, called the *stethoscope*,‡ the object of which is to render audible the action of the heart and the neighboring organs. It consists of a

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* Herschel.

† Arnott's El. Phys. I, 497.

‡ στῆθος, *the chest*; σκοπέω, *to examine*.

wooden cylinder, one end of which is applied firmly to the breast, while the other end is brought to the ear. By this means, the processes that are going on in the organs of respiration, and in the large blood vessel about the heart, may be distinctly heard; and it is said that the stethoscope, when skillfully used, "becomes the means of ascertaining some diseases in the chest, almost as effectually as if there were convenient windows for visual inspection."*

636. Chladni and Jacquin, of Vienna, a few years since, made some experiments with a view to determine the sonorous properties of different *gases*.† A vessel being exhausted of common air and furnished with a bell, various gases were successively introduced and their effects on the sound of the bell noted. A mixture of nitrogen and oxygen gases in the *same proportions* as that in which they form atmospheric air, gave the same sound as air; but when mixed in different proportions, the sound was varied accordingly. Pure oxygen gas gave sounds from nine to eleven tones higher than common air; in carbonic acid gas, the tones were lower; but in hydrogen, the tones are much more acute.‡

Reflexion of Sound.

637. Sounds are *reflected* by hard bodies, producing the well known phenomenon called an ECHO. If a straight line be drawn from the sounding body to the reflecting surface representing the course of the sound before reflexion, and another straight line be drawn from the reflecting surface, in the direction of the sound after reflexion, these two lines will make equal angles with that surface; that is, when sound is reflected, *the angle of reflexion is equal to the angle of incidence.*

638. The surfaces of various bodies, solids as well as fluids, have been found capable of reflecting sounds, viz. the sides of hills, houses, rocks, banks of earth, the large trunks of trees, the surface of water, especially at the bottom of a well, and sometimes even the

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* Dr. Arnott. † Haüy's Nat. Phil. I, 308,—*Note.*

‡ Arnott, I, 495.

clouds.* It is therefore evident that in an extensive plain, or at sea, where there is no elevated body capable of reflecting sounds, no echo can be heard. It is hence easy to see why the poets, who convert Echo into an animated being, place her habitation near mountains, rocks, and woods.†

639. An echo is heard when a person stands in a position to hear both the original and the reflected sound; and the interval will be greater or less according to the distance of the reflecting surface from the sounding body and from the hearer, and hence the interval may be made a measure of the distance. If the sound of the voice returns to the speaker in two seconds, the distance of the reflecting surface is one thousand one hundred and forty two feet, and in that proportion for other intervals. Thus, the breadth of a river may be ascertained when there is an echoing rock on the farther shore. A perpendicular mountain's side, or lofty cliffs, such as frequently skirt the sea coast, sometimes return an echo of the discharge of artillery, or of a clap of thunder, to the distance of many miles.‡ The number of syllables that can be pronounced in half the interval, will be repeated distinctly; but a greater number would be blended with the commencement of the echo.§

640. When a single obstacle reflects the sound, the echo is *simple;* when there are several obstacles disposed at suitable distances, the echo is *complex*. Echoes of the latter kind have been observed which repeated the original sound forty times.|| Two parallel walls which mutually reverberate the sound, may produce a double or complex echo, with regard to an auditor placed in the intermediate space. The sound of artillery and of thunder, is frequently prolonged by reverberations in an uneven country.

641. The furniture of a room, especially the softer kind, such as curtains or carpets, impair the qualities of sound by presenting surfaces unfavorable to vibrations. A crowded audience has a similar effect and increases the difficulty of speaking. Halls for music

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* Cavallo, II, 345. † Haüy. ‡ Arnott.

§ Cavallo, II, 347. || Haüy.

or declamation, should be constructed with plain bare walls. Alcoves, recesses, and vaulted ceilings produce reverberations which often greatly impair the distinctness of elocution. Indeed the qualities of a room, in regard to sound, are modified by so many circumstances,* that the science of acoustics is worthy of more attention from the architect than it has generally received. Plane and smooth surfaces reflect sound without dispersing it, convex surfaces disperse it, and concave surfaces collect it. The concentration of sound by concave surfaces, produces many curious effects both in nature and art. There are remarkable situations where the sound from a cascade is concentrated by the surface of a neighboring cave, so completely, that a person accidentally bringing his ear into the focus, is astounded by a deafening noise. Sound issuing from the center of a circle is, by reflexion, returned to the center again, producing a very powerful echo.† Such effects are observed in the central parts of a circular hall. An elliptical apartment conveys sound very perfectly from one focus to the other. A whisper uttered by a person in one focus of such a chamber, will be audible to a person in the other focus, though not heard by persons between.

642. *Whispering Galleries*‡ are constructed on this principle. Domes, as that of St. Paul's Cathedral, in London, sometimes ex-

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* The famous Dr. Saunderson, formerly Professor of Mathematics in the University of Cambridge, who had been blind from the time he was a year old, possessed such acuteness of hearing, that he not only distinguished persons with whom he had ever once conversed so long as to fix in his memory the sound of their voice, but he could also recognize places by observing the manner in which they modified sound. He could judge accurately of the size of a room, and of his distance from the wall; and if ever he had walked over a pavement in courts, or piazzas, and was conducted thither again, he could tell his exact situation, by the note which the place sounded.

† If a spherical room could be constructed of perfectly solid materials, perfectly polished, and a sound were to issue from the voice of a person in the center, there would be an accumulation of echo at the center, which would probably be destructive of the organs of hearing. —*Latrobe in Ed. Encyc.*

‡ The *Hall of Secrets*, as it is called, in the Observatory at Paris, is a whispering gallery. This hall is of an octagonal form, with

hibit the same curious property.* Concave surfaces facing each other, as two alcoves in a garden, or covered recesses on opposite sides of a street or bridge, will enable persons seated in their foci to converse by whispers, notwithstanding louder noises in the space between, and without themselves being overheard in that space.† A notorious instance of a sound-collecting surface, was the *ear of Dionysius*, in the dungeons of Syracuse. The roof of the prison was so formed as to collect the words, and even whispers of the unhappy prisoners, and to direct them along a hidden conduit to the place where the tyrant sat listening. The wide spread sail of a ship, rendered concave by a gentle breeze, is also a good collector of sound. Dr. Arnott‡ relates an instance where the ringing of the bells at St. Salvador on the coast of Brazil, was heard on board a ship at the distance of one hundred miles from land.

643. The most frequent instances of the reflexion of sound, are from surfaces which may be considered as plane. In these, the sound issuing from any point seems, after reflexion, to proceed from a point equally distant, and similarly situated, on the other side of the reflecting surface; the phenomena differing a little according to the position of the speaker, with respect to the body which occasions the reflexion. If a person's voice strike any surface perpendicularly, it will be reflected back in the same line; and the time occupied between the utterance of the sound, and its arrival again at the speaker, will be equal to the time in which the sound travels through twice the distance between the speaker and the reflecting surface. The interval, therefore, between setting out and returning will be found by the following rule. Let x=the intervals in seconds, and d=twice the distance from the sounding body to the reflecting surface; then $1 : 1142 :: x : d \therefore x = \frac{d}{1142}$. If, therefore, the distance

cloister arches, or arched by portions of a cylinder, which meet at angles, corresponding to those formed by the sides of the building. The speaker applies his mouth very near to the wall to one of the angles, and the person situated at the opposite angle hears his voice distinctly.

* Cavallo. † Arnott. ‡ El. Phys. I, 505.

is less than forty eight feet, the interval of time between the speaker's hearing the direct and the reflected sounds, will be less than $\frac{1}{11}$ of a second, and the two sounds will seem to coalesce and form but one sound; but if the distance exceeds forty eight feet, then the interval will be greater than $\frac{1}{11}$ of a second, and as this interval can be discerned by the ear, the two sounds will be separate, and will form an echo.*

644. The rolling of thunder has been attributed to echoes among the clouds; and that such is the case has been ascertained by direct observation on the sound of cannon. Under a perfectly clear sky, the explosion of guns is heard single and sharp, while, when the sky is overcast, or when a large cloud comes over head, the reports are accompanied by a continued roll, like thunder, and occasionally a double report arises from a single shot.†

645. The continued sound of distant thunder, which is sometimes prolonged for many seconds, is not always owing to reverberation, but frequently arises simply from the different distances of the same flash. Although the progress of a flash of lightning through the air were absolutely instantaneous, still, if its path were in a line that would carry it farther from the ear in one place than in another, there would be a corresponding difference in the times at which the sound generated in different portions of the path would reach the ear. Herschel observes, that if (as is almost always the case) the flash be zigzag, and composed of broken rectilinear and curvilinear portions, some concave, some convex to the ear; and especially, if the principal trunk separates into many branches, each breaking its own way through the air, and each becoming a separate source of thunder, all the varieties of that awful sound are easily accounted for.‡

646. The *Speaking Trumpet* has been supposed by most writers on sound, to owe its peculiar properties, to its multiplying sound by numerous reflexions. Hence is suggested the form of a parabolic conoid, or a tube, the section of which is a parabola, the place of the mouth

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* Edinburgh Encyc. Art. *Acoustics.* † Herschel.

‡ Herschel on Sound, Encyc. Metrop. II, 754.

being at the focus of the parabola. The vibrations emanating from the mouth would then be reflected into straight lines parallel with the axis of the trumpet, and would thus go forward in a collected body to a distant point.* And, since such a form is also favorable for collecting distinct sounds into one point, the same figure is proposed as most suitable for the *Ear Trumpet*. But the sound of these instruments may be regarded as merely the longitudinal vibration (Art. 613.) of a body of air, to which momentum is given in the direction of the axis, not by reflexion from the sides but by the direct impulse of the mouth.† The ancients were acquainted with the speaking trumpet. Alexander the Great is said to have had a horn, by means of which he could give orders to his whole army at once.‡

647. Sound may be conveyed to a much greater distance by being confined, during its whole transmission, within a pipe. Pipes used for this purpose are called *Acoustic Tubes*. Such tubes are frequently employed in public houses for conveying orders to the attendants. Dr. Herschel employed a similar tube attached to his forty feet telescope, for communicating his observations to an assistant, who sat in a small house near the instrument; and thus, under cover, noted them down, and the particular time in which they were made. Acoustic tubes are commonly of a cylindrical form, and have at each extremity a mouth-pipe like that of a speaking trumpet, to which either the mouth or ear is applied, according as the person is speaking or listening to another. In the deception called the *Invisible Girl*, the sound of the voice is transmitted and returned through acoustic tubes.

648. *Ventriloquism* does not, as is frequently supposed, depend on the reflexion of sound, but wholly on the inaccuracy with which the ear judges of the direction from which sound proceeds; enabling the performer by a variation of his tone of voice, and by seeming not to move his lips, to persuade the spectators that the sound proceeds from some object to which he has diverted their attention. The imitations of different sounds by which the ventriloquist is able to perso-

* Dr. Young, Nat. Phil. I, 375.

† Ed. Encyc. II, 118.

‡ Enfield's Scient. Rec. p. 157.

nate a variety of characters, and to represent them as engaged in an animated dialogue with each other, are usually limited to a comparatively small number, which have been acquired and rendered very familiar by long practice. Hence, like the performer on a musical instrument, he makes his transitions from one sound to another with a facility which can be acquired only by the force of habit.

649. *Sounding Boards* were formerly constructed over the desks of public speakers, particularly in churches, with the view of aiding the powers of the voice. Their efficacy depended on the reflexion of the sound; for, being near the speaker, the echo or reflected sound, uniting itself with the direct sound, would augment its force or loudness. In stringed instruments, however, as the violin, the sounding board acts by receiving vibrations from the string. Thus by impelling the air with a greater surface, it produces a more powerful sound than the string alone. Hence, if some weight (called a *mute*,) as a penknife partly open, be attached to the bridge of a violin, the sound is greatly deadened, the vibrations of the string being thus prevented from extending to the sounding board.*

650. The concave, undulating, and perfectly polished surface of many sea shells, fits them to catch, to concentrate, and to return the pulses of all sounds that happen to be trembling about them, so as to produce that curious resonance from within, which resembles the distant murmur of the ocean.† The organs of speech and of hearing have a mechanical structure most skilfully adapted to the peculiar nature of sound.

The *human voice* depends principally on the vibrations of the membranes of the *glottis*, excited by a current of air which they alternately interrupt and suffer to pass; the sounds being also modified in their subsequent progress through the mouth.‡

651. The parts of the ear, and the progress of sound to the sentient nerve, may be simply described as follows.

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* Ed. Encyc. II, 119. † Arnott.

‡ Young's Lectures, I, 401.

Fig. 117.

(1.) There is externally a wide mouthed tube or ear trumpet *a* for catching and concentrating the pulses of sound. In many animals it is movable, so that they can direct it to the place from which the sound comes.

(2.) The sound concentrated at the bottom of the ear-tube, falls upon a membrane stretched like the top of an ordinary drum, over the tympanum or drum of the ear, *b*, and causes it to vibrate. That its motion may be free, the air contained within the drum has free communication with the external air by the open passage *f*, called the ***Eustachian tube***, leading to the back of the mouth. A degree of deafness ensues when this tube is obstructed by wax.

(3.) The vibrations of the tympanum are conveyed further inwards by a chain of four bones, (not here represented on account of their minuteness) reaching from the centre of the tympanum to the oval door or window of the *labyrinth e*.

(4.) The labyrinth, or complex inner compartment of the ear, over which the nerve of hearing is spread as a lining, is full of water; and therefore, when the vibrations of the tympanum acting through the chain of bones (3.) are communicated to this fluid, they are instantly felt over the whole cavity (Art. 446.) The labyrinth consists of the *vestibule e*, the three *semicircular canals c*, imbedded in the hard bone, and of a winding cavity *d* called the *cochlea*, like that of a snail shell, in which fibres, stretched across like harp-strings, constitute the *lyra*. The exact uses of these various parts are not yet perfectly known. The membrane of the tympanum may be pierced, and the chain of bones may be broken, without loss of hearing.*

Philosophical Principles of Music.

652. On this subject, we have room for only a few leading principles.

When separate sounds are repeated with a certain degree of frequency, the ear loses the power of distinguishing the intervals, and

* Dr. Arnott, *El. Phys.* Vol. I, p. 507.

they appear united in one continued sound. By this means also sounds harsh and dissonant in themselves, form a soft and agreeable tone. Any sound whatever repeated not less than thirty or forty times in a second, excites in the hearer the sensation of a musical note. Nothing is more unlike a musical sound than that of a quill drawn slowly across the teeth of a coarse comb; but when the quill is applied to the teeth of a wheel whirling at such a rate that 720 teeth pass under the quill in a second, a very soft, clear note is heard.* In like manner the vibrations of a long harp-string, while it is very slack, are separately visible, and the pulses produced by it in the air are separately audible; but as it is gradually tightened, its vibrations quicken, and the eye soon sees, when it is moving, only a broad shadowy plane; the distinct sounds which the ear lately perceived, run together, owing to the shortness of the intervals, and are heard as one uniform continued tone, which constitutes the note or sound proper to the string.†

Nature presents us with numerous examples of a musical sound produced by the rapid succession of an individual sound, not at all musical in itself. The hum of winged insects, produced by the frequent motion of their wings, the murmur of a forest occasioned by the agitation of the leaves and boughs, and the sublime roar of the ocean constituted of the separate sounds produced by innumerable waves, are familiar examples of the operation of this principle.

653. *Musical intervals*, or sounds differing from each other in pitch by a certain interval, are found by experience to be peculiarly agreeable to the human ear, a fact for which we can assign no reason except that such is the constitution of the mind.‡ Birds may sometimes exhibit a fine voice; but their singing is not musical, having nothing to do with musical intervals.§

Musical sounds have certain *ratios* to one another, and are thus brought into the province of Mathematics, because the number of vibrations which produce one musical note, has a constant ratio to the number which produces another musical note. Thus, if we dimin-

* Robison's *Mech. Phil.* IV, 404. † Arnott.

‡ Playfair's Outlines, I, 274. § Cavallo.

ish the length of a musical string one half, we double the number of its vibrations in a given time, (Art. 612.) and it gives a sound eight notes higher in the scale than that given by the whole string. Therefore, these sounds are represented by the numbers 2 and 1, and are said to be in the ratio of 2 to 1. The upper note is said to be the *octave* of the lower; and from its great resemblance to the *fundamental* note, or that afforded by the whole string, it is considered as the commencement of a repetition of the same series; so that all audible sounds are considered as repetitions of a series contained within the interval of an octave.*

654. The length of the entire string being called 1, the respective lengths of the strings which sound the eight notes, are, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, $\frac{1}{2}$. The sound given by the whole string, which is denoted by 1, is called the *key* note, and the other notes are called, respectively, the second, third, fourth, fifth, sixth, seventh, and eighth, and the fractions denote the relation of each note in the scale to the key note. Since the number of vibrations is inversely as the length of the string, (Art. 612.) these fractions inverted will express the number of vibrations which produces the several notes of the scale respectively. Thus $\frac{9}{8}$ denotes that the string which sounds the next note above the key note vibrates 9 times, while the whole string vibrates 8 times. Hence the series expressing the number of vibrations which produce the notes of the scale, are $\quad 1, \frac{9}{8}, \frac{5}{4}, \frac{4}{3}, \frac{3}{2}, \frac{5}{3}, \frac{15}{8}, 2.$

But, on reducing these numbers to a common denominator, and taking their numerators, (which express the ratios of the fractions,)† we have the following series,

$$24, 27, 30, 32, 36, 40, 45, 48.$$

Hence, we have the following proposition.

***If a string be divided, so that the number of vibrations performed by each part in a given time, shall be in the ratio respectively of the numbers* 24, 27, 30, 32, 36, 40, 45, 48, *the sounds of the first seven will be perceived as increasing in acuteness one above another, from the first to the last, and will yield the notes from the combinations of which all musical effects are produced.*‡**

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* Young, II, 393. † Day's Algebra, Art. 360, Cor. 1.

‡ Playfair's *Outlines*, I, 273.

655. By inspecting the last series of numbers, namely, that which expresses the relation between the successive notes of the diatonic scale, we shall perceive that the ratios between two successive numbers, and of course the intervals between the several notes of the scale, are not all equal to each other.

1.	The ratio of	27 to 24	is that of	9 : 8
2.	"	30 to 27	"	10 : 9
3.	"	32 to 30	"	16 : 15
4.	"	36 to 32	"	9 : 8
5.	"	40 to 36	"	10 : 9
6.	"	45 to 40	"	9 : 8
7.	"	48 to 45	"	16 : 15

Hence it appears that there are in the musical scale three sorts of intervals, of which three bear to the fundamental or key note the ratio of 9 to 8, two that of 10 to 9, and two more that of 16 to 15. The first of these intervals being the largest, is denominated the *major tone*, the second the *minor tone*, and the third the *semitone*. The scale therefore is made up of three major, two minor, and two semitones, as represented in the table.

656. After ascending through the first seven notes of the scale, we arrive, as has been already intimated, (Art. 653.) at a note which seems to be only a repetition of the first; hence it commences a new series of seven notes analogous to the former series, each note being an *octave* above the corresponding note in that series, and therefore implying vibrations twice as rapid. A third series is constituted in the same manner, called the *double octave*, in which the lengths of the string are $\frac{1}{4}$ of those in the first part of the scale.

657. All musical sounds are computed to be contained between *ten octaves;* so that the number of vibrations in a given time that yields the gravest note, is to that which yields the most acute, as 1 to 2^{10}, that is, as 1 : 1024.*

658. When the vibrations are less numerous than about 16 per second, the ear loses the impression of a continued sound, and per-

* Playfair's *Outlines*, I, 274.

ceives, first, a fluttering noise, then a quick rattle, then a succession of distinct sounds capable of being counted. On the other hand, when the frequency of the vibrations exceeds a certain limit, all sense of *pitch* is lost; a shrill squeak, or chirp, only is heard; and, what is very remarkable, many individuals, no way inclined to deafness, are altogether insensible to very acute sounds, even such as painfully affect others. This singular observation is due to Doctor Wollaston.* Nothing can be more surprising than to see two persons, neither of them deaf, the one complaining of the penetrating shrillness of a sound, while the other maintains that there is no sound at all.† Few musical instruments comprehend more than six octaves, and the human voice has only from one to three, the male voice being in pitch an octave lower than the female.‡

659. The intervals of the diatonic scale, are denoted by the first seven letters of the alphabet, A, B, C, D, E, F, G; which are repeated usually in small letters *a*, *b*, *c*, &c. in the higher series.

A succession of single musical sounds, constitutes *melody;* the combination of such sounds, at proper intervals, forms *chords;* and a succession of chords constitutes *harmony*. Two notes produced by an equal number of vibrations in a given time, and of course giving the same sound, are said to be in *unison*. The relation between a note and its octave is, next after that of the unison, the most perfect in nature; and when the two notes are sounded at the same time, they almost entirely unite.§ The fifth (Art. 654.) constitutes the next most perfect chord, while the second and the seventh are peculiarly harsh discords. By examining the scale of vibrations in Art. 654, we shall perceive that the chords are characterized by frequent *coincidences of vibration*, while in the discords such coincidences are more rare. Thus in the unison, the vibrations are perfectly isochronous; in the octave the two coincide at the end of every vibration of the longer string, the shorter meanwhile performing just two vibrations; and in the fifth, they coincide at the end of every two vibrations of the longer string, the shorter vibrating three times in the same

* Phil. Transac. 1820.

† Herschel.

‡ Arnott, *El. Phys.* I, 481.

§ Ed. Encyc. Art. *Music*.

period. But in the second, the longer and shorter vibrations can coincide only after eight of the longer and nine of the shorter, and in the seventh, only after eight of the longer and fifteen of the shorter. Hence the concord is more perfect as the common period is shorter.*

Musical intervals therefore are divided into *chords* and *discords*. The octave, the major fifth, the major and minor thirds, the major and minor sixths, are concords, and are pleasing in themselves. The seconds, the sevenths, the minor fifth and major fourths, are discords. The chord consisting of the fundamental note with its third and fifth, and called the harmonic triad, forms the most perfect harmony, and contains the constituent parts of the most simple and natural melodies.†

660. *Discords*, however, are employed in musical composition; but their use is limited by special rules. Of the occasion and manner of introducing them, the following extract from Burney's History of Music, will give the learner a general idea. "While harmony was refining and receiving new combinations, it was found, like other sweet and luscious things to want qualification to keep off languor and satiety, when some bold musician had the courage and address to render it piquant and interesting, by means of discords, in order to stimulate attention; and thus by giving the ear a momentary uneasiness, and keeping it in suspense, its delight became the more exquisite, when the discordant difficulty was solved. Discord in musical composition, however, does not consist in the excess or defect of intervals, which, when false, produce jargon, not music; but in the warrantable and artful use of such combinations as, though too disagreeable for the ear to dwell upon, or to finish a musical period, yet so necessary are they to modern counterpoint, and modern ears, that harmony without their relief, would satiate, and lose many of its beautiful effects."

661. When a long string is made to vibrate, there are heard not only the note belonging to the whole length of the string, but also more feebly the subordinate notes belonging to its half, its third, its

* Young's N. Phil. I, 391. † Young.

fourth, &c. thus giving to a single sound the effect of harmony. Hence such subordinate sounds are called, with respect to the principal sound, its *Harmonics*. Often the subordinate sounds swell with such force as to overpower for a time the fundamental note; and then if the string be carefully examined, it will be found to be vibrating, not as a whole, but in two, three, or four, distinct portions, with points of rest between them.* The sounds thus belonging to a single string, and produced by its spontaneous division into different numbers of equal parts, constitute, when heard together or in succession, the simple music of nature herself. It is produced in the most perfect manner by the *Æolian Harp*.

662. Hence arises what is denominated the *sympathy of sounds*. If two cords equally stretched, and in all other respects similar, but one only half, one third, or some other aliquot part of the length of the other, be placed side by side, and the shorter be struck or sounded, the vibration will be communicated to the longer by the intervention of the air, which will thus at once be thrown into a mode of vibration in which the whole length is divided into segments, each equal to the shorter string. Here the vibrations imparted to the string that is struck, are communicated to the aërial pulsations, which will impress on any body *capable of vibrating in their own time* an actual vibratory motion; and if a body is susceptible of a number of modes of vibration performed in different times, that mode only will be excited which is *synchronous with the aërial pulsations*. All other motions, though they may be excited for a moment by one pulsation, will be extinguished by a subsequent one. Hence, if two cords have any mode of vibration in common, that mode may be excited by sympathy in either of them when the other is sounded, and that only. For example, if the length of one cord is to that of the other as 2 : 3, and if either be set vibrating, the mode of vibration, corresponding to a division of the former into two, and of the latter into three segments, will, if it exists in the one, be communicated by sympathy to the other. In the vibrations of cords, which from their small sur-

* Arnott, *El. Phys.* I, 478; Young's *Nat. Phil.* I, 382; Haüy's *Nat. Phil.* I, 316.

face can receive but a trifling impulse from the air, the sounds and motions excited by this sort of sympathetic communication are feeble; but in vibrating bodies which present a large surface, they become very great. It is a pretty well authenticated feat performed by persons of clear and powerful voice, to break a drinking-glass by singing its proper fundamental note close to it. Looking-glasses also are said to have been occasionally broken by music, the excursions of their molecules in the vibrations into which they are thrown being so great as to strain them beyond the limits of their cohesion.*

663. The theory of *Musical Instruments* will be readily understood from the principles already explained. It will be seen that they all owe their power of producing musical sounds to their susceptibility of vibrations; that the force or loudness of the sounds they afford depends on the *length* of the vibrations, and the graveness or acuteness of the sound, in other words the pitch, on their *slowness* or *frequency;* and that their chords depend, in general, upon *frequency of coincidence in the vibrations* that afford the several sounds of the concord.

664. The nature of stringed instruments may be learned from the *violin.* Here the strings are of the same length, but differ in weight and tension; those designed to afford the lower notes being heavier and less strained, and those for the higher notes being lighter and more tense. The lengths, moreover, are altered by applying the fingers. The several strings are usually so adjusted to each other, that is, so *tuned*, that any two contiguous strings make a *fifth*. Hence the fourth or highest stop on one string brings it into unison with the string above; and the third stop on any string forms an octave with the open string next below. On account of this power of altering the effective lengths of the strings at pleasure, of developing the harmonic sounds by a skilful application of the fingers, and of varying constantly the degrees of fullness or force in each sound by a dexterous use of the bow, the violin becomes in the hands of an accomplished performer, an instrument of great power and compass, while it is capable of greater variety than any other musical instrument.

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* Herschel on Sound.

665. The *flute* affords an example of wind instruments. Here the vibrating body is a column of air to which different lengths are given by means of the stops which are opened and closed by the fingers. The rapidity of the vibrations, and consequently the pitch, is also changed a whole octave by the management of the breath.

In mixed wind instruments, the vibrations or alternations of solid bodies are made to cooperate with the vibrations of a given portion of air. Thus, in the trumpet, and in horns of various kinds, the force of inflation, and perhaps the degree of tension of the lips, determines the number of parts into which the tube is divided, and the harmonic which is produced. The hautboy and clarionett have mouth-pieces of different forms, made of reeds or canes; and the reed-pipes of an organ, of various constructions, are furnished with an elastic plate of metal, which vibrates in unison with the column of air which they contain. An organ generally consists of a number of different series of pipes, so arranged, that, by means of registers, the air proceeding from the bellows may be admitted to supply each series, or excluded from it at pleasure; and a valve is opened when the proper key is touched, which causes all the pipes belonging to the note, in those series of which the registers are open, to sound at once. These pipes are not only such as are in unison, but frequently also one or more octaves above and below the principal note, and sometimes also twelfths and seventeenths, imitating the series of natural harmonics.*

* Young's Lects. I, 402.

PART IV.—ELECTRICITY.

666. ELECTRICITY is a term derived from ἤλεκτρον, the Greek word for *amber*,* that being the substance in which a property of the agent now denominated Electricity was first observed.

The ancient Greek philosophers were acquainted with the fact that amber, when rubbed, acquires the property of attracting light bodies; hence the effect was denominated *electrical*; and, in later times, the term *Electricity* has been used to denote both the unknown *cause* of electrical phenomena, and the *science* which treats of electrical phenomena and their causes.

667. The science of Electricity is hardly more remarkable on account of its surprising and beautiful phenomena, than it is curious in its *history*. The first observation recorded of it was made by Thales of Miletus,† who ascribed it to the functions of some hidden animal.‡ Theophrastus,§ the natural historian, mentions a stone called *lyncurium* (supposed to be the *tourmalin* of modern mineralogists) possessing the property of attraction as well as amber. He observes that it is said not only to attract straws and small pieces of sticks, but even copper and iron, if they be finely divided.‖ This is near-

* Amber is a resinous substance having the appearance of indurated honey. It sometimes naturally exhibits the shape of water-worn pebbles. When heated it exhales a highly agreeable odor. From its scarcity it bears a high price. Much of the amber found in the market is brought from Prussia, where it is found in mines, or loosely scattered along the sea coast; and it is found in other countries, imbedded in a peculiar kind of sand and gravel.

† Sometimes styled the "father of Grecian philosophy." Flourished 600 years before the Christian era.

‡ Priestley's History of Electricity, p. 1.

§ Lived at Athens, 300 years B. C.

‖ Τὸ λυγκούριον ἕλκει γὰρ ὥσπερ τὸ ἤλεκτρον. οἱ δέ φασιν οὐ μόνον κάρφη καὶ ξύλον, ἀλλὰ καὶ χαλκὸν καὶ σίδηρον, ἐὰν ᾖ λεπτός· ὥσπερ καὶ Διοκλῆς ἔλεγεν. —Theophrastus περὶ τῶν λίθων.

ly the amount of what was known of Electricity by the ancients; nor, so far as is known, was there a single important fact added to this science for the period of nineteen centuries.

668. In the year 1600, Dr. Gilbert, an English philosopher, published a work on Magnetism, comprising also many observations on Electricity. He knew nothing more of this agent, however, than as a power of attraction. Little was added to the knowledge of *Gilbert* on this subject until the latter part of the same century, when, after the establishment of the Royal Society of London, and of the Academy of Sciences at Paris, philosophical experiments began to be prosecuted with a zeal before unknown. *Boyle** discovered a number of interesting facts in Electricity, and *Otto Guericke*† constructed the first electrical machine, using a globe of sulphur, instead of the glass cylinder at present employed.

But the first sixty years of the eighteenth century, may be remembered as the period when the greatest discoveries in Elec-

* Honorable Robert Boyle, an English philosopher, lived in the reign of Charles the Second and flourished about the year 1670. He was one of the founders of the Royal Society of London, and was a very zealous and diligent experimentalist, and distinguished for his virtues and piety. Though the facts discovered by Boyle were valuable contributions to the science, yet it may serve to show the absurd notions which prevailed at that time on points of theory, to recite his veiws of electrical attraction. He supposed that an excited body emitted a glutinous effluvium, which laid hold of small bodies in its way, and, in its return to the body which emitted it, carried them back with it.—*Priestley's Hist. Elec. p. 7.*

† Otto Guericke of Magdeburg in Germany, better known as the inventor of the air-pump. He was contemporary with Boyle, and united an inventive talent with a taste for philosophical experiments. His electrical machine conisted of a globe of sulphur made by melting that substance in a hollow globe of glass, and then removing the glass by breaking it. This globe he mounted upon an axis, and whirled it in a wooden frame, rubbing it at the same time with his hand. Guericke first observed the electric spark.

tricity were made. *Grey** in England, *Du Fay*† in France, and *Franklin*‡ in America, are the names most distinguished in the history of this period. Each of these individuals made numerous and important discoveries; and the last two severally proposed hypotheses to account for the phenomena of electricity, hypotheses which have ever since divided the opinions of electricians.

For the sake of convenience, the term *electric fluid* is employed, without however, implying any thing more than the *unknown cause* of electrical phenomena, whatever that cause may be.

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* Stephen Grey a pensioner of the British government—flourished about the year 1730—made numerous discoveries, the most important of which was the division of bodies into *conductors and non-conductors.*

† Du Fay, was a member of the Academy of Sciences at Paris,—flourished about the year 1733—he discovered, among other things, the influence of *moisture* upon the conducting power of bodies—the fact that *electrified* attract *unelectrified* bodies—and the *two different kinds of Electricity*, the vitreous and resinous or positive and negative.

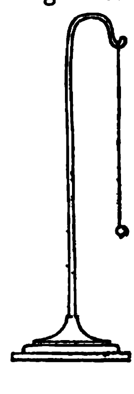
‡ Dr. Franklin commenced his labors in electricity in 1747. The results of his experiments and observations were communicated in several letters addressed to Peter Collinson, Esq. of London, Fellow of the Royal Society, written at different times from 1747 to 1754. "Nothing (says Dr. Priestley's *Hist. Elec. page* 159.) was ever written upon the subject of Electricity, which was more generally read and admired in all parts of Europe than these letters. There is hardly any European language into which they have not been translated; and, as if this was not sufficient to make them properly known, a translation of them has lately been made into Latin. It is not easy to say, whether we are most pleased, with the simplicity and perspicuity with which these letters are written, the modesty with which the author proposes every hypothesis of his own, or the noble frankness with which he relates his mistakes, when they were corrected by subsequent experiments."

CHAPTER I.

OF THE GENERAL PRINCIPLES OF THE SCIENCE.

669. The most general effect by which the presence of electricity is manifested is *attraction*. Thus, when a glass tube is rubbed with a dry silk or woollen cloth, it acquires the property of attracting light bodies, as cotton, feathers, &c. When, by any process, a body is made to give signs of electricity, it is said to be *excited*. When a body receives the electric fluid from an excited body, it is said to be *electrified*. Since there is found to be a great difference in bodies in regard to the power of transmitting electricity, all bodies are divided into two classes CONDUCTORS and NON-CONDUCTORS. *Conductors* are bodies through which the electric fluid passes readily; *non-conductors* are bodies through which the electric fluid either does not pass at all, or but very slowly. The latter bodies are also denominated *electrics*, because it is by the friction of bodies of this class that electricity is usually excited. An electrified body is said to be *insulated*, when its connexion with other bodies is formed by means of non-conductors, so that its electricity is prevented from escaping. Instruments employed to detect the presence of electricity are denominated *electroscopes*; such as are employed to estimate its comparative quantity, are called *electrometers*. This distinction however is neglected by some writers, and, to avoid the unnecessary multiplication of terms, it will be neglected in the present treatise, instruments of either kind being called *electrometers*.

Fig. 118.

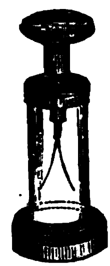


670. The *Pendulum Electrometer* is formed by suspending some light conducting substance by some non-conducting substance. Thus, *a small ball of the pith of elder hung by a silk thread*, constitutes a very convenient instrument for detecting the presence and examining the kind of electricity. Figure 118 represents a pendulum electrometer, consisting of a glass rod fixed in a stand, and bent at the top so as to form a hook. From this hook hangs a thread of raw silk, to the bottom of which is attached a small pith ball, made smooth and round, and weighing only a small

part of a grain. The attenuated thread of silk, unwound from the ball of the silkworm, forms a very delicate insulator; but for ordinary purposes, a common thread of silk may be untwisted, and a single filament taken for the suspending thread. For the purposes of the learner, it may even be sufficient to suspend a ball of cork, or a lock of cotton, or a feather by a thread of silk.

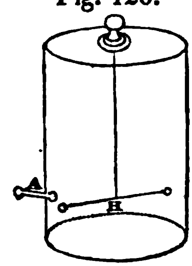
671. The *Gold Leaf Electrometer*, represented in Fig. 119, consists of two strips of gold leaf suspended from the metallic cover of a small glass cylinder. By this arrangement, the pieces of gold leaf are insulated, they are protected from agitation by the air, and Electricity is easily conveyed to them by bringing an electrified body into contact with the cover. The approach of an electrified body causes the leaves to separate, or when previously separated, to collapse according to principles to be explained presently.

Fig. 119.



672. *Coulomb's Electrometer*, Fig. 120, is an apparatus of still greater delicacy and perfection than either of the preceding instruments. It consists of a cylindrical glass vessel having also a lid of glass, in the center of which a small hole is drilled. Through this hole passes an untwisted raw silk thread four inches long, and fixed at the top to a micrometer, by means of which it may be turned round any number of degrees at pleasure. To the silk thread is attached a very fine thread of lac, H, having at each extremity a small pith ball. This lac needle with its knobs weighs only one fourth of a grain. A small hole is drilled in the side of a vessel at A, through which passes a fine wire terminated at both extremities by a knob. When an excited body is placed in contact with the knob at A, the knob at the other extremity will acquire the same electricity as the excited body. This electricity it will communicate to the knob of the lac needle, suspended by the silk thread, which was previously almost in contact, and the two knobs will repel each other. The movable knob attached by the silk thread will separate from the

Fig. 120.



other, and the quantity of electricity will be proportional to the distance to which it recedes.*

By the aid of the foregoing instruments, or even by means of the pendulum electrometer alone, we may ascertain the following LEADING FACTS, which are so many fundamental truths, in the science of Electricity.

673. PROP. I. *Electricity is produced by the Friction of all bodies.*

Although friction is the most common, and by far the most extensive means of exciting bodies, yet it is not the only means. Electricity is manifested during the *changes of state* in bodies, such as liquefaction and congelation, evaporation and condensation. Some bodies even are excited by mere *pressure;* others by the *contact* or *separation of different surfaces.* Most *chemical combinations and decompositions* are also attended by the evolution of Electricity, which manifests its presence to delicate electrometers.

If we rub a piece of amber, sealing wax, or any other resinous substance, on dry woollen cloth, or fur, or silk, and bring it towards an electrometer, it will give signs of electricity. A glass tube may be excited in a similar manner. Moreover if we bring the excited tube near the face, it imparts a sensation resembling that produced by a cobweb. If the tube is strongly excited, it will afford a spark to the knuckle, accompanied by a snapping noise. A sheet of white paper, first dried by the fire, and then laid on a table and rubbed with India rubber, will become so highly excited as to adhere to the wall of the room, or any other surface to which it is applied. Indeed friction is so constantly attended by Electricity, that in favorable weather the fluid is abundantly indicated on brushing our clothes, which thus are made to attract the light downy particles that are floating in the air.

674. Our proposition asserts that Electricity is produced by the friction of *all* bodies, whereas if we hold in the hand a metallic substance, a plate of brass or iron, for example, and subject it to friction,

* Thomson's Outlines of Heat and Electricity, p. 374.

we shall not discover the least sign of electrical excitement. In such cases, however, the Electricity is prevented from accumulating in consequence of the substance being a *good conductor*, and thus conveying the fluid to the hand, which is another good conductor, by which means it is lost as fast as it is excited. But if we insulate a metallic body, or any other conducting substance, then on being rubbed, it gives signs of Electricity, like electrics.

Liquids and gases, by friction against solid bodies, excite Electricity. Thus quicksilver agitated in a glass tube electrifies it, and the blast of a bellows against the projecting knob of Coulomb's electrometer, (see fig. 120) puts the needle in motion. Even a slight puff with the mouth, directed upon the knob will produce a sensible degree of excitation.

675. PROP. II. *The Electricity which is excited from* GLASS *and a numerous class of bodies, exhibits different properties from that which is excited from* AMBER, *or sealing wax, and a class of bodies equally numerous with the other.*

The kind of fluids excited from glass and analogous bodies is called *vitreous*, and that from amber and analogous bodies, *resinous* Electricity. The term *positive* is also used instead of vitreous, and *negative* instead of resinous.

In order to understand the applications of the preceding terms *vitreous* and *resinous*, *positive* and *negative*, it is necessary to know something of the two hypotheses upon which these terms are respectively founded. The first hypothesis is that proposed by *Du Fay*.* It ascribes all electrical phenomena to the agency of *two* fluids specifically different from each other, and pervading all bodies. In unelectrified bodies, these two fluids exist in combination, and exactly neutralize each other. By the separation of the two fluids it is that bodies are electrified, and it is by the re-union of the two fluids, that the Electricity is discharged, or bodies cease to be excited. The second hypothesis was proposed by Dr. Franklin. It ascribes all electrical phenomena to the agency of *one* fluid, which, as in the oth-

* This is sometimes called the Hypothesis of *Symmer*, after an English electrician of that name who matured and illustrated the principle first suggested by Du Fay, (See Phil. Trans. 1759.)

er case is supposed to pervade all bodies, being naturally in a state of equilibrium. It is only when this equilibrium is destroyed that bodies become electrified, and it is by the restoration of the equilibrium that the Electricity is discharged, or bodies cease to be excited. But a body is electrified when it has either more or less of the fluid than its natural share; in the former case it is *positively*, in the latter case *negatively*, electrified; positive Electricity therefore, implies a redundancy and negative Electricity, a deficiency of the fluid.

This much being sufficient for the understanding of the terms, and of the general principles of these two celebrated hypotheses, we shall postpone all discussions respecting them, until the learner has become acquainted with a sufficient number of electrical phenomena to enable him to understand and to judge of the evidence adduced in support of each hypothesis.

676. Prop. III. *Bodies electrified in different ways attract, and in the same way repel each other.*

Thus if an insulated pith ball (Art. 670.) or a lock of cotton, be electrified by touching it with an excited glass tube, it will immediately recede from the tube, and from all other bodies which afford the vitreous Electricity, while it will be attracted by excited sealing wax, and by all other bodies which afford the resinous Electricity. If a lock of fine, long hair be held at one end, and brushed with a dry brush, the separate hairs will become electrified, and will repel each other. In like manner, two insulated pith balls, or any other light bodies will repel each other when they are electrified the same way, and attract each other when they are electrified different ways.

Hence it is easy to determine, *whether the Electricity afforded by a given body is vitreous or resinous;* for, having electrified the electrometer by excited glass, then all those bodies which, when excited, *attract* the ball, afford the resinous, while all those which *repel* the ball afford the vitreous Electricity.

677. Prop. IV. *The two kinds of Electricity are produced simultaneously; the one kind in the body rubbed, the other in the rubber.*

For example, if we rub a glass tube with a silk or woollen cloth, the glass becomes positive, and the cloth negative. The foregoing

law holds true universally; but the kind of Electricity which each substance acquires, depends upon the substance against which it is rubbed. If we rub dry woollen cloth against *smooth* glass, it acquires the resinous, and the glass, the vitreous Electricity; but if we rub the same cloth against *rough* glass, it becomes positively, while the glass becomes negatively electrified.* The following table contains a number of electric substances, arranged in such a way that when they are rubbed against each other, any substance in the list before another becomes positively, and any substance below it negatively, electrified.

1. Fur of a Cat,	6. Paper,
2. Smooth Glass,	7. Silk,
3. Woollen Cloth,	8. Lac,
4. Feathers,	9. Rough Glass,
5. Wool,	10. Sulphur.

The fur of a cat, when rubbed against any of the bodies in the table, always affords the vitreous, and the sulphur always the resinous electricity. Feathers become negative when rubbed against the fur of a cat, smooth glass, or woolen cloth; but positive when rubbed against wool, paper, silk, lac, rough glass, or sulphur.†

678. Prop. V. *Electricity passes through some bodies with the greatest facility; through others with the greatest apparent difficulty, or scarcely at all; and others have a conducting power intermediate between the two.*

Metals and charcoal, water and all liquids (oils excepted) are good conductors. *Melted* wax and tallow are good conductors; but these bodies while solid conduct very badly. Glass, resins, gums, sealing wax, silk, sulphur, precious stones, oxides, air, and all gases, are non-conductors, or at least very bad conductors.‡ Atmospheric air is a

* The cloth should be attached to a glass handle to insulate it.

† When black stockings are worn over white, numerous sparks are frequently observed on pulling off the outer pair. The same appearances occur, when a silk garment is worn over flannel. (See an interesting account of Symmer's experiments on this subject in Priestley's History of Electricity, p. 267.)

‡ Thomson.

non-conductor of the highest class, when perfectly dry; but it becomes a conductor, either when moist or when rarefied. The electric fluid easily pervades the vacuum of an air pump, or of the Torricellian tube (Art. 539.); but these are imperfect vacuums; it is said that Electricity cannot pass through a perfect vacuum.*

680. The conducting powers of most bodies are influenced by changes of temperature, and also by changes of form. Water, in its natural state, is a good conductor; but its conducting power is increased by heat and diminished by cold. Steam and ice are each inferior, in conducting power to pure water; and ice below the temperature of —13° Fah. becomes an electric of the highest class. Snow, when cold and dry, is a bad conductor. During a dry snow storm the air frequently becomes highly electrical.

The same body frequently exhibits great changes in conducting power by changes of state, or chemical constitution. Thus, green wood is a conductor, dry baked wood a non-conductor; charcoal a conductor, ashes a non-conductor.

681. Strictly speaking there is no substance known, that is entirely impervious to Electricity; for the intensity of that agent may be so increased as to force it, for a greater or less distance, through all bodies. Neither is there any body in which the conducting power is perfect. The following table presents a catalogue of bodies arranged in the order of their conducting powers.

CONDUCTORS.

Metals, the more perfect, or least oxidable the better.
Charcoal, better when prepared from hard wood and well burned.
Plumbago.
Acids, strong mineral acids best.
Charcoal in fine powder.
Salts, in solution.
Metallic Ores.
Animal Fluids.
Pure Water.
Ice, at common temperatures.

* Lib. Use. Knowl. Art. Electricity, p. 5.

Snow, better when moist, worse when dry.
Living vegetables.
Living animals.
Flame, Smoke, Steam.
Salts, not in solution.
Rarefied Air.
Vapor of Alcohol, or Ether.
Earths and Stones.
Pulverized Glass.
Flowers of Sulphur.

NON-CONDUCTORS OR ELECTRICS.

Lac, Amber, Resins.*
Sulphur.
Wax.
Fat.
Glass, Gems, Precious Stones.
Silk, Wool.
Hair, Feathers.
Cotton, Paper.
Leather.
Sugar, refined and crystallized.
Dry Atmospheric Air, and other gases.
Baked Wood.
Porcelain, Hard stony Bodies.
India Rubber.
Dry Chalk, Lime.
Phosphorus.
Ice, below —13° Fah.
Crystals, when dry and transparent.

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* Lac, which is placed at the head of non-conductors, is a species of resin, sold by the druggists, and is deposited upon a tree in India by a certain species of insects.—*Shell lac*, the most common form employed in electrical experiments, is nothing more than lac in its purest form.—*Sealing wax* is substituted for lac in electrical experiments, being made chiefly of that substance.—*Varnishes*, also, which are employed to coat the surfaces of electrical apparatus, owe their efficacy to lac of which they are chiefly composed.

Ashes.
Oils.
Dry Metallic Oxides.

It is particularly important to remember that Metals, Water and all moist substances, Animal substances, as the human body, and the Earth itself, are *conductors;* while the Air, when dry, and all Resinous and Vitreous substances are *non-conductors.* These bodies are those which are chiefly concerned in making experiments with electrical apparatus.

682. PROP. VI. *Insulation is effected in various degrees of perfection, according to the state of the atmosphere, and the nature of the substances employed as insulators.*

If the air were a conductor, it is not easy to see how the electric fluid could be confined so as to be accumulated. It is, moreover, only when the air is *dry* that it is capable of insulating well; hence, in damp, foggy, and rainy, weather, electrical apparatus will not work well, unless the air is dried artificially by operating in a close room highly heated by a stove.*

683. Lac, drawn into fine threads, is the most perfect insulator. Compared with silk thread, such a filament is ten times more effectual in preventing the loss of the fluid. Fine silk thread, however, when perfectly dry, is among the best insulators, and where great delicacy is required, a single filament of silk as it comes from the ball of the silk worm is employed. Its conducting power is somewhat influenced by its color, black being the worst, and a gold yellow the best color for insulating. Glass is much used as an insulator, especially when great strength is required, as in supports to various kinds of electrical apparatus. Glass, however, is liable to acquire moisture on its surface, in consequence of which its properties as an insulator are materially impaired. This inconvenience is obviated by giving it a thick coat of varnish. Fine hair is a good and convenient substance in some cases of insulation.

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* We have been able to hold public lectures on Electricity, illustrated by numerous experiments, in the most unfavorable weather, by keeping the room highly heated by close stoves.

In some cases conducting or uninsulating threads are required. Then fine silver wires or linen threads, first steeped in a solution of salt and dried, are used.

684. The *sphere of communication* is the space within which a spark may pass from an electrified body, in any direction from it. It is sometimes called the striking distance. The *sphere of influence* is the space within which the power of attraction of an electrified body extends in every way, beyond the sphere of communication. A glass tube strongly excited will exert an influence upon the gold leaf electrometer at the distance of ten or even twenty feet, although a spark could not pass from the tube to the cap of the electrometer at a greater distance than a few inches.

685. The electricity which a body manifests by being brought near to an excited body, without receiving a spark from it, is said to be acquired by *Induction*.

When an insulated conductor, unelectrified, is brought into the neighborhood of an insulated charged conductor, its Electricity undergoes a new arrangement. The end of it next to the excited conductor, assumes a state of electricity opposite to that of the excited conductor; while the farther extremity assumes the same kind of electricity. Suppose the excited conductor, is electrified positively. The end of the insulated conductor next to it, becomes negative, and the remoter end positive; and intermediate between these two points, there occurs a place where neither positive nor negative electricity can be perceived. This place is called the *neutral point*.

The reason why unelectrified bodies are attracted by excited electrics is, that they are put into the opposite state by induction, and then attracted upon the general principle laid down in Prop. III. When they come into the sphere of communication of the excited body, they immediately acquire the same kind of electricity, and are repelled. If they come into contact with uninsulated bodies they lose the electricity they have acquired, are again put into the opposite state by induction, again attracted and again repelled. This process will go on until the electricity of the insulated conductor is all conveyed away.*

* Thomson's Outlines of Heat and Elec. p. 362.

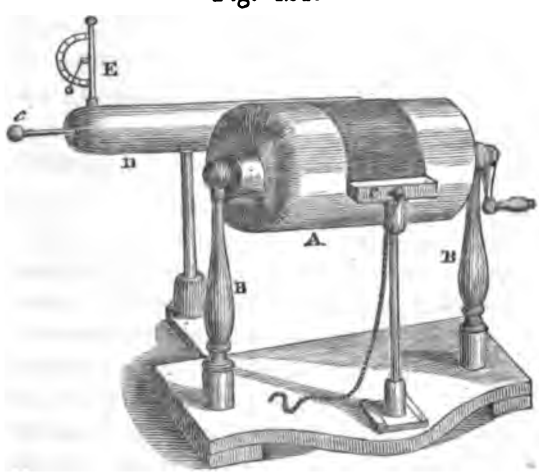
The foregoing general principles may be verified with very simple apparatus such as pith balls, a glass tube, and a stick of sealing wax. But the same facts may be exhibited in a much more striking and impressive manner by the electrical machine and its appendages, and our attention will therefore be now turned to the consideration of the subject of electrical apparatus.

CHAPTER II.

OF ELECTRICAL APPARATUS.

686. The object of the electrical machine is to *accumulate* electricity. It is made of several different forms, but two of these forms are predominant, which it will be sufficient for our present purpose to describe; of these one is called the Cylinder, the other, the Plate machine. The CYLINDER MACHINE is represented in figure 121.

Fig. 121.



The principal parts belonging to it, are the cylinder, the frame, the rubber, and the prime conductor. The *cylinder* (A) is of glass, from eight to twelve inches in diameter, and from twelve to twenty four inches long. It should be perfectly cylindrical, otherwise it

will not press the cushion or rubber evenly when turned. It must be as smooth as possible, for rough glass becomes a partial conductor; the latter only is suitable for affording positive electricity. The cylinder should be so mounted on the frame as to revolve without waddling, for such a motion would prevent its being in uniform contact with the rubber. The *Frame* (B B) is made of wood, which must be close grained, well seasoned, and baked in an oven, and finally coated with varnish, the object of all this preparation being to diminish its conducting powers, and thus prevent its wasting the electricity of the cylinder. The *Rubber* (C,) consists of a leathern cushion, stuffed with hair like the padding of a saddle. This is covered with a black silk cloth, having a flap which extends from the cushion over the top of the cylinder to the distance of an inch from the points connected with the prime conductor, to be mentioned presently. The rubber is coated with an amalgam* made of mercury, zinc, and tin, which preparation has been found, by experience, to produce a high degree of electrical excitement, when subjected to the friction of glass. The rubber is insulated by placing it on a solid glass pillar, and it is made to fit closely to the cylinder by means of a spring worked by a screw.

The *Prime Conductor* D, is usually a hollow brass cylinder with hemispherical ends. It is mounted on a solid glass pillar, with a broad and heavy foot made of wood to keep it steady. The cylinder is perforated with small holes, for the reception of wires (*c*) with brass knobs.

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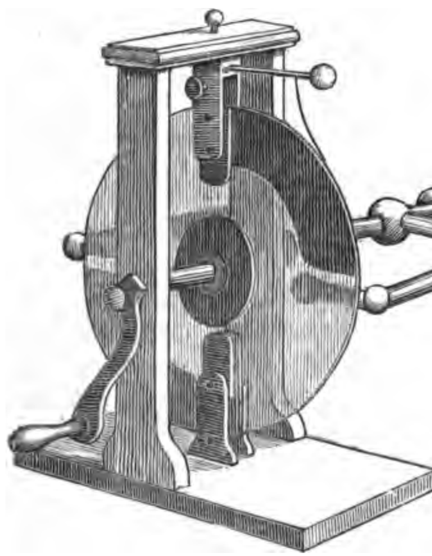
* The amalgam recommended by Singer, one of the ablest practical electricians, is composed of zinc two ounces, of tin one ounce, and of mercury six ounces. The zinc and tin may be melted together in a ladle or crucible, and poured into a mortar, previously heated to prevent the sudden congelation of the melted metals. As soon as they are introduced, they must be rapidly stirred with the pestle, during which process the mercury may be added, and the stirring continued until the amalgam is cold, when it will be in the form of paste or fine powder. A little lard is added, to give the amalgam the proper consistence; but if, when applied, it be warmed a little, but a small proportion of lard need be used. In hot weather, less quicksilver is to be employed.

It is important to the construction of an electrical machine, that the work should be smooth and free from points and sharp edges, since these have a tendency to dissipate the fluid, as will be more fully understood hereafter. For a similar reason the machine should be kept free from dust, the particles of which act like points, and dissipate the electricity.

687. The PLATE MACHINE (Fig. 122.) consists of a circular plate of glass from eighteen to twenty four inches or more in diam-

Fig. 122.



eter, turning vertically on an axis that passes through its center. The frame is composed of materials similar to those which compose the frame of the cylindrical machine. This machine is furnished with two pairs of rubbers, attached to the top and bottom of the plate. The prime conductor consists of a brass cylinder, proceeding from the center in a line with the axis, and having two branches which serve to increase its surface, and at the same time to connect it with the opposite sides of the plate, so as to receive the Electricity as it is evolved from each cushion.

It is not agreed which of these two machines affords the greatest quantity of Electricity from the same surface; but the cylinder is

less expensive than the plate, and less liable to break, and is more convenient for common use.

688. The principles of the electrical machine, will be readily comprehended from what has gone before. It differs from the glass tube, only in affording a more convenient and effectual mode of producing friction. By the friction of the glass cylinder or plate against the rubber, electricity is evolved, which is immediately transferred to the prime conductor, and may be taken from the latter by the knuckle, or any other conducting substance. If the glass and the rubber both remain insulated, the quantity of Electricity which they are capable of affording, will soon be exhausted. Hence, a chain or wire is hung to the rubber and suffered to fall upon the table or the floor, which, communicating as it does with the walls of the building, and finally with the earth, supplies an inexhaustible quantity of the fluid to the rubber. In cases where very great quantities of electricity are required, a metallic communication may be formed immediately between the rubber and the ground.

689. In order to indicate the degree of excitement in the prime conductor, the *Quadrant Electrometer* is attached to it, as is represented at E in figure 121. This electrometer is formed of a semicircle, usually of ivory, divided into degrees and minutes, from 0° to 180°,* the graduation beginning at the bottom of the arc. The index consists of a straw, moving on the center of the disk, and carrying, at the other extremity, a small pith ball. The perpendicular support is a pillar of brass, or some conducting substance. When this instrument is in a perpendicular position and not electrified, the index hangs by the side of the pillar, perpendicularly to the horizon; but when the prime conductor is electrified, it imparts the same kind of electricity to the index, repels it, and causes it to rise on the scale towards an angle of 90°, or to a position at right angles with the pillar. It is obvious that the index can never rise higher than 90°, since the knob which terminates the brass pillar is electrified to the

* Sometimes the division is carried only to 90°, which is all that is necessary.

same degree as the prime conductor, and repels the index with equal force. Nor is the angle at which the index remains suspended to be regarded as the true measure of the repulsive force. It has been demonstrated, that, in order to estimate this force truly, the arc of the electrometer should be divided according to a scale of arcs, the tangents of which are in arithmetical progression.*

690. When an electrical machine is skillfully fitted up, and works well, on turning it, circles of light surround the cylinder or plate, and brushes or pencils of light emanate copiously from the cushion and other parts of the machine. The circles of light consist of electric sparks, which discharge themselves between the excited surface and the rubber, their passage being so rapid as to appear like a continued line, like that of a small stick ignited at the end and whirled in the air. The brushes of light arise from the facility with which the fluid escapes from points or thin edges.

The experiments which were previously performed on electrical attractions and repulsions, (Arts. 669—678.) may now be repeated in

* Partington's Manual Nat. Phil. II, 157.

As electrical machines are expensive, and not always easily procured by the private learner, it may be useful to suggest a mode of fitting up a cheap apparatus. A large tincture bottle may be procured of the apothecary, for the cylinder. A cover of wood may be cemented to each end, to the center of which, next to the bottom, is screwed a projecting knob for one end of the axis, while the part of the axis to which the handle is attached, is screwed into the center of the cover of wood next to the nozzle. Thus prepared, it may be mounted on such a frame of hard dry wood as every joiner or cabinet maker can construct. A tinner can make the prime conductor, and several other appendages to be described hereafter. Junk bottles or long phials serve well as insulators. Ingenious students of electricity, frequently amuse themselves with making machines of this description, some of which have answered nearly every purpose of the most expensive kinds of apparatus.

A *cement*, for electrical purposes, may be made by melting together five ounces of resin, one ounce of bees' wax, one ounce of Spanish brown, and a tea spoonful of plaster of Paris, or brick dust.

a much more striking manner, and various other experiments added, which can be shown only when electricity is accumulated.

691. We proceed to enumerate a few of the effects of electricity as they are exhibited by the electrical machine, confining ourselves, for the present, to those experiments which relate to attraction and repulsion, and the passage of the spark, reserving such as relate to light and heat to future sections. The following effects may be observed with a machine of moderate powers, the rationale of which the learner will readily supply from the propositions given in Art. 683, &c.

(1.) When the machine is turned, a downy feather, or a lock of cotton held in the hand by a conducting thread,* will be strongly attracted towards the excited surface.

(2.) A skein of thread, or lock of fine hair, looped, and suspended by the loop from the prime conductor, will exhibit strong repulsions between the threads or hairs.

(3.) The quadrant electrometer being attached to the prime conductor, the conducting powers of different substances may be readily tried. Thus, an iron rod held in the hand, and applied to the prime conductor, will cause the index of the electrometer to fall instantly; and the same effect will follow the application of any metallic rod. A wooden rod of the same dimensions, will cause the index to descend more slowly; and a glass rod will hardly move it at all. These experiments show that iron is a perfect, and wood an imperfect conductor, and glass a non-conductor. In the same manner the conducting powers of a stick of sealing wax, a roll of silk, or cloth, and of various other bodies, may be illustrated.

(4.) If a pith ball, or feather, or any other light body, held by a silk thread, be presented to the prime conductor, it will first be attracted and then repelled, and it cannot again be brought into contact with the electrified conductor, until its electricity is discharged by communicating with the finger, or some unelectrified conductor.

(5.) By placing light bodies between an electrified conductor and an uninsulated body, they may be made to move with great rapidity backwards and forwards, from one surface to the other, being alter-

* The conducting power of linen or cotton threads is improved by moistening them with the breath.

nately attracted and repelled by the electrified surface. By this means are performed electrical dances, the ringing of bells, and a variety of interesting and amusing experiments.*

(6.) If the rubber be *insulated* while the machine is turned, the rubber and the glass cylinder, or plate will be found to be in different electrical states; an insulated body attracted by the one will be repelled by the other.

Bodies are electrified positively by connecting them with the glass, by means of the prime conductor, and negatively by connecting them with the rubber, the latter being insulated, and the prime conductor uninsulated.

(7.) An electrified body frequently exhibits a tendency to separate into minute parts, these parts being endued with the power of mutual repulsion. Thus, a lock of cotton, when electrified, is separated into its minutest fibres. Melted sealing wax, when attached by a wire to the prime conductor, is divided into filaments so small as to resemble red wool. Water dropping from a capillary syphon tube, on being electrified, is made to run out in a great number of exceedingly fine streams. Water spouting from an air fountain (Art. 535.) is divided into a number of rays, presenting the appearance of a brush.

(8.) A portion of electrified air, in consequence of the mutual repulsion between its particles, expands, and when at liberty to escape, becomes rarefied. Thus, a current of air may be set in motion from an electrified point, or small ball, or be made to issue from the neck of a bottle.

Such are some of the leading experiments which may be performed with the common electrical machines, in addition to those which are connected with light and heat, to be more particularly described hereafter.

Torsion Balance.

692. The instrument called the Torsion Balance, invented by Coulomb,† exceeds all others in delicacy and the power of measur-

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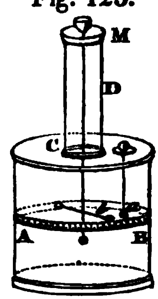
* See *Singer's Elements of Electricity*, for a good selection of these experiments.

† Charles Augustus Coulomb, was a very distinguished member of the French Academy, and remarkable for his assiduity and precision in experimental researches. He flourished during the latter part of

ing small forces; and in the skillful hands of the inventor, it furnished the means of very refined investigations into the most hidden laws of electricity. The same instrument also applied to similar researches in several other branches of physics, affording in each case an example of the most refined experimental analysis.

693. The force employed to estimate any given power of electric attraction, is the force of *torsion*; that is, the effort made by a twisted thread or wire to untwist itself. Since the thread may be small to any extent, and may be of any length, (and the force of torsion is found to be inversely as the length, and directly as the fourth power of the thickness†) the degrees by which this force is increased as the thread is turned, may differ from each other by the smallest conceivable quantity, and yet be separated by spaces far enough asunder to be susceptible of being measured with the utmost precision; and thus any force, as that of electrical attraction required to hold the successive degrees of the force of torsion in equilibrium, may be exactly ascertained. If by a fine thread (which may be either the smallest filament of silk, or the finest silver wire) we suspend a horizontal needle, as in the electrometer represented in figure 120, the least conceivable force applied at the extremities of the needle, will put it in motion. A lever an inch long, suspended by a fibre of silk four inches in length, requires a force only the sixty thousandth part of a grain, to twist it three hundred and sixty degrees.

Fig. 123.



994. The construction of the instrument is as follows. In order to guard the suspended needle from the agitations of the air, it is protected by a glass cylinder A B, having a movable lid C, from the center of which rises a smaller glass cylinder D, which covers the suspending thread, this latter cylinder is surmounted by a graduated circle M, upon which moves a pointer or index, connected at the center with the suspending thread which is

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the last century. His experiments on electricity, magnetism, friction and the resistance of fluids, are among the finest in natural philosophy.

† Biot, Précis El. tome I. 339.

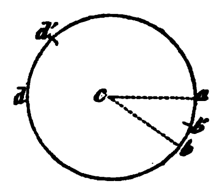
twisted when the index is turned. The lid C is perforated with a hole to allow access to the pith ball of the needle. In the figure this opening is represented as closed by the handle of a movable rod of glass or lac, which insulates the ball *a*, by which electricity is conveyed to the ball *b* of the needle. On a level with the needle is a circular band graduated into degrees and minutes. It is usually made of paper and pasted around the cylinder.

695. To prepare the apparatus for experiments, the index on M is set opposite to zero, and then the circle, conveying the index along with it, is turned until the ball of the needle rests opposite to zero, on its graduated circle. In this situation, the suspending thread is entirely untwisted or free from torsion. Now let the ball *a*, be electrified, by receiving a spark from the prime conductor, and let it be introduced to the level of the needle. The ball *b*, of the needle, being unelectrified, is first attracted to the electrified ball, imbibes the same kind of electricity, and is then repelled to a greater or less distance, according to the intensity of the electricity. On account of the extreme delicacy of the instrument, only a very small charge must be applied; otherwise the agitation of the needle will be in danger of breaking the thread,* or the arc described by the needle, will be inconveniently large. The charge is therefore applied from a pin's head, the pin itself being concealed in sealing wax. The pin's head being electrified, it is touched by the ball *a*, by means of which the charge is introduced into the cylinder and made to communicate with the ball *b*, of the needle. Suppose the force of repulsion between the two balls to be such, that the needle will finally settle at the distance of 36° from zero, or the point where it was quiescent. It would describe a greater arc in that direction, were not its motion counteracted by the force of torsion exerted by the suspending wire.

* The filament used by Coulomb in some of his experiments, was a silver wire, a foot of which weighed only the one sixteenth of a grain.

696. Our object, it will be recollected, is to estimate the forces of this repulsion at different distances from the electrified ball *a*. This is done by finding the relative forces of torsion, required to bring those respective forces of repulsion to an equilibrium. We therefore turn the index upon the circle M, in a direction opposite to that in which the needle moved, and observe the number of degrees through which the index must be turned, in order to make the ball *b*, approach to any given distance of the ball *a*. Coulomb proceeded as follows. The ball *b* being electrified by contact with *a*, receded from it, describing an arc of 36°. The index on the circle M was then turned in the opposite direction, until the needle was carried back to the distance of 18°, which required the index to be turned over 126°. Again the index was turned until the needle was brought to the distance of 8½°, which required it to be turned over 567°. Let *a b d* represent the circle in which these movements were performed, *c* being its center. Take *a b* equal to 36°, then the *b* will be the position of the needle after the first repulsion. The index which carries the thread, being now turned backwards 126°, the ball *b*, were it free to move, would be carried over the same arc to *d′*, 126° beyond *a*; but, on account of the repulsion of the ball *a*, it stops short at *b′* at the distance of 18° from *a*. Therefore, the force of repulsion of the two balls, is 126°+18°=144°. In the third case, where the index was turned 567°, and the needle brought to the distance of 8½° of *a*, were it not for the repulsion between the balls, the needle would have been carried 567° beyond *a* to *d*, but stops short of *a* 8½°; therefore, that repulsion is equal to 567°+8½=575½°. Hence the respective forces of repulsion exerted at the several distances were as follows:

Fig. 124.



Distances.	Repulsive forces.
36°	36 which are 1 : 1.
18°	144 " " ½ : 4.
8½°	575½ " " ¼ : 16.

It appears that the distances are to one another nearly in the ratio of the numbers 1, ½, ¼, while the corresponding forces are as 1, 4, 16; that is, *the force of repulsion between two electrified bodies, at*

*different distances, varies inversely as the square of the distance.** The same law therefore governs the electrical forces as that which prevails among the bodies of the solar system.

697. Analogous experiments prove that attraction obeys the same law. Some practical difficulty was experienced by Coulomb, in his experiments on attraction, since, when the balls are differently electrified, as they must of course be in experiments on attraction, they will come together if brought within moderate distances of each other. But the law was satisfactorily shown to hold good, at such distances as were susceptible of measurement, and the law was farther established by a process totally different from the preceding. It consisted in bringing the suspended needle near to an insulated electrified sphere, by which it is made to oscillate with greater or less rapidity according to its degree of proximity. The number of oscillations, in a given time, is a measure of the force of attraction, as the number of oscillations of the pendulum measures the force of gravity, being, universally, as the square roots of the forces. (Art. 255.) The proposition may, therefore, be stated in general terms.

The force of electrical attraction or repulsion, at different distances from an electrified body, varies inversely as the square of the distance.

Rate at which charged bodies lose their electricity.

698. It is a well known fact, that when an insulated conductor, charged with electricity, is suffered to remain untouched for a certain time, it will gradually lose its charge. Now since, in some of the delicate researches of Coulomb, a considerable time was necessarily occupied, the electrified bodies under examination might change their degree of excitement during the experiments, and thus give a fallacious result. It became important therefore, to ascertain the law according to which this dissipation or loss of electricity took place, and to make suitable allowance for it.

699. Three causes chiefly operate in depriving a body under these circumstances of its electricity :—first, the imperfection of bodies em-

* Biot, Précis Elém. tome I, 482.

ployed as insulators; secondly, the contact of successive portions of air, every particle of which carries off a certain quantity of the fluid; thirdly, the presence of moisture, which increases the conducting powers of all surfaces. (Art. 681.) No substance is absolutely impervious to electricity; that is, there is no substance known of which any portion, however small, will insulate perfectly any charge however great. Still, by diminishing the intensity of the charge, or by increasing the length of the substance it has to traverse, a degree of insulation may be obtained in which the escape of the fluid is imperceptible. This tendency of electricity to escape from charged bodies, is independent of the chemical nature of those bodies, being the same, under similar circumstances, for balls of wax, copper, elder pith, and various other substances. The same tendency is equally independent of the shape, and magnitude of bodies, unless when the intensity of the charge is high; in which case, a figure that involves points and edges favors the dissipation of the fluid. When bodies are highly charged, the electricity is lost with comparative rapidity; more slowly as the charge is less; and, the air being dry, and the insulator of a proper length, a certain charge will be retained without further loss.*

But the chief source of dissipation of the electric charge, arises from moisture, either existing in the air, or settling upon the surface of the insulating supports, or imbibed into the fibres of insulating threads.

Distribution of Electricity.

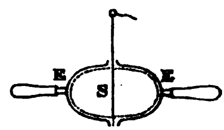
700. Does Electricity reside only at the surfaces of bodies, or is it expanded throughout the whole of their substance? Coating a conductor with some non-conducting substance, (as a wire with sealing wax, leaving the ends naked,) does not in the least impede the passage of the fluid through it. Indeed, every conductor may be considered as really, in this situation, being in contact with a stratum of air on every side, which, when dry, is a good non-conductor. The conclusion from this fact is, that the passage of the fluid is not confined to the surface, mathematically considered, but must, at least,

* Lunn, Encyc. Metrop.

occupy the exterior *stratum* of the conductor. It was found, however, by Coulomb, that if, of two bodies of equal surface and similar form, as two equal spheres, one be electrified, and the other be brought into contact with it, the electricity will be equally divided between them, and that this takes place when one sphere is solid and the other hollow, equally as when both spheres are solid. Hence it is inferred, that electricity resides only at or very near the surfaces of bodies.

701. This fact is strikingly illustrated by an experiment, proposed by M. Biot.* Let S, (Fig. 125.) represent any spheroid of conducting matter, suspended by a thread of some perfectly insulating substance. Let EE be two caps formed of gilt paper, tin foil, or any other conductor, and such that when united, they accurately fit the surface of the spheroid. An insulating handle of lac is also attached to each of the caps. Now let there be communicated to the ball S, any degree of electricity, and then carefully apply to it the two caps, holding them by their insulating handles. Upon removing these caps, it will be found that every particle of electricity has been abstracted from the spheroid, so that it will no longer affect the most delicate electrometer; while the two caps will be found, upon accurate trial, to have acquired precisely the same quantity of electricity which before resided upon the body S.

Fig. 125.



702. A proof of this point, equally conclusive, and applicable to bodies of every form, was devised by Coulomb. An insulated, solid conductor, of any figure, being provided, cavities were dug in it, to different depths below the surfaces, and in several different places, and the body was electrified. A *proof plane*, as it was called, consisting of a small circle of gilt paper, to which was attached an insulating handle of lac, was introduced into these various cavities, and applied to the bottom of them. It was then withdrawn, and tested by the electrometer, and not the slightest trace of electricity was in-

* Précis Elém. tome I, p. 498.

dicated. In these experiments, care was taken to introduce the proof plane, in such a way as not to touch the edges of the cavities, or any part of the surface, the object being to ascertain whether signs of electricity were exhibited at any depth below the surface. The conclusion was, that there were none, and consequently that the electricity of excited bodies resides wholly at the surface.

703. An experiment, which may be easily repeated, shows how much the intensity of an electric charge is affected by the extent of surface which it pervades. Let a sheet of tin foil be wrapped several times around an insulated cylinder, which is mounted so as to turn horizontally on an axis. Upon unwinding the metallic sheet, and thus increasing the extent of electrified surface, an electrometer connected with the cylinder will indicate a decline in the intensity of the charge, at every successive enlargement of surface.

704. Although Electricity resides at the surface of an electrified body, yet it is not distributed *uniformly* over that surface, except the body be a perfect sphere, but is unequally accumulated, in different parts of the surface, in a manner depending on the figure of the body. The principle may be enunciated in general terms, thus:—

In conductors of an elongated figure, the electricity is accumulated towards the two ends, and withdrawn more or less from the central parts.

Coulomb, in his investigations on this subject, employed the *proof plane*, (Art. 702.) the circle of gilt paper being so small as to bear no considerable ratio to the surface of the electrified body under examination. By touching this plane to different points of the surface, the plane imbibes the charge belonging to that point, and may be made to transfer it to the balls of the electrical balance. (Fig. 123.) Then the amount of torsion required to bring the balls to the same given distance of each other, will be a measure of the charge communicated to the balls in each case; that is, the torsions will indicate the ratios existing between the different charges of electricity, at different points in the surface of the body under examination.

705. In this manner, Coulomb determined the distribution of electricity upon a steel plate, eleven inches long, one inch broad, and half a line thick, insulated and electrified. In order to cover the breadth of the plate, the gilt paper was made an inch long, but very narrow. First, the proof plane was applied to the center of the plate, and at one inch from the extremity; the latter charge was to the former as 1.2 to 1, and therefore nearly equal. Secondly, on applying the plane quite at the extremity, the charge was to that at the center as 2 to 1. Thirdly, the plane was applied, at one end, to the extreme edge, so as to be in contact with both surfaces; in which case, the charge was double that of each extreme surface, and of course, four times that of the central parts.

706. Hence it appears, that the electricity of a conductor, analogous to the steel plate employed in the foregoing experiments, is nearly uniform on all parts of the surface, except the two ends, where it becomes twice as great as in the other parts. The rapid increase of electricity towards the extremities, appears also in other bodies of an elongated figure; and the augmentation is the more rapid, as the length is greater in respect to the diameter; and when the extremity becomes elongated, like the point of a cone, the accumulation at that extremity becomes so great, that the resistance of the air is not sufficient to retain it, and it escapes, producing the electric spark. Hence the reason why points, connected with an electrified conductor, dissipate the fluid so rapidly.

The limited extent of this work, will not permit us to give a more particular account of the researches of Coulomb, carried on by the aid of the Torsion Balance; but we would recommend these researches, as detailed by Biot,* to the student of Natural Philosophy, as examples of the most refined, ingenious, and conclusive experiments.

* Précis Eléméntaire de Physique, tome I.

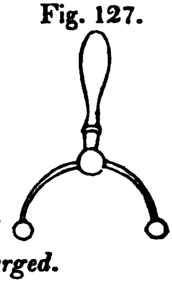
CHAPTER III.

OF THE LEYDEN JAR.

707. This instrument, which is a very important and interesting article of electrical apparatus, consists of a glass jar, coated on both sides with tin foil, except a space on the upper end, within two or three inches of the top, which is either left bare, or is covered with a coating of varnish, or a thin layer of sealing wax. To the mouth of the jar is fitted a cover of hard baked wood, through the center of which passes a perpendicular wire, terminating above in a knob, and below in a fine chain, that rests upon the bottom of the jar. On presenting the knob of the jar near to the prime conductor of an electrical machine, while the latter is in operation, a series of sparks passes between the conductor and the Jar, which will gradually grow more and more feeble, until they will cease altogether. The Jar is then said to be *charged*. If now we take the *Discharging Rod*, (which is a crooked wire, armed at each end with knobs, and insulated by a glass handle, as in Fig. 127,) and apply one of the knobs to the outer coating of the Jar, and bring the other to the knob of the Jar, a flash of intense brightness, accompanied by a loud report, immediately ensues. On applying the discharging rod a second time, a feeble spark passes, being the *residuary charge*, after which all signs of electricity disappear, and the Jar is said to be *discharged*.

Fig. 126.

Fig. 127.



708. If, instead of the discharging rod, we apply one hand to the outside of the charged Jar, and bring a knuckle of the other hand to the knob of the Jar, a sudden and surprising *shock* is felt, convulsing the arms, and, when sufficiently powerful, passing through the breast.

709. The Leyden Jar derives its name from the place of its discovery. In the year 1746, while some philosophers of Leyden were performing electrical experiments, one of them happened to hold, in one hand, a tumbler partly filled with water, to a wire, connected with the prime conductor of an electrical machine. When the water was supposed to be sufficiently electrified, he attempted, with the other hand, to detach the wire from the machine; but as soon as he touched it, he received the electric shock. It was by imitating this arrangement, that the Leyden Jar was constructed; for here was a glass cylinder, having good conductors on both sides, viz. the hand on the outside, and water on the inside, which were prevented from communicating with each other by the non-conducting powers of the glass. A metallic coating, as tin foil or sheet lead, was substituted for the two conductors, and a jar for the glass cylinder, and thus the electrical jar was constructed.

710. Those who first received the electric shock from the Leyden Jar, gave the most extravagant accounts of its effects. M. Muschenbroeck, a philosopher of Leyden, of much eminence, said that "he felt himself struck in his arms, shoulders, and breast, so that he lost his breath; and it was two days before he recovered from the effects of the blow and the terror; adding, that he would not take a second shock for the kingdom of France." M. Winkler, of Leipsic, testified, that "the first time he tried the Leyden experiment, he found great convulsions by it in his body; and that it put his blood into great agitation, so that he was afraid of an ardent fever, and was obliged to use refrigerating medicines. He also felt a heaviness in his head, as if a stone lay upon it, and twice it gave him a bleeding at the nose."

711. In an age less enlightened than the present, and less familiar with the wonders of philosophy and chemistry, the striking and truly surprising effects of Electricity, as exhibited by the Leyden Jar, would naturally excite great admiration and astonishment. Accordingly, showmen travelled with this apparatus through the principal cities of Europe, and probably no object of philosophical curiosity ever drew together greater crowds of spectators. It was this astonishing experiment, (says Dr. Priestley,) that gave eclat to Electricity. From this time, it became the subject of general conversation. Every body was

eager to see, and, notwithstanding the terrible account that was reported of it, to *feel* the experiment; and in the same year in which it was discovered, numbers of persons, in almost every country in Europe, got a livelihood by going about and showing it. All the electricians of Europe, also, were immediately employed in repeating this great experiment, and in attending to the circumstances of it.* With similar assiduity and unequalled success, Dr. Franklin betook himself to experiments on the Leyden Jar. He effectually investigated all its properties, by very diversified and ingenious experiments, and gave the first rational explanation of the cause of its phenomena. The following experiments may be easily repeated.

712. (1.) *The Jar is charged by bringing the knob near the prime conductor, while the machine is in operation.* One mode of charging the Jar has been already mentioned in Art. 707. It may, however, either be held in the hand, or placed on the table, or on any conducting support: the only circumstance to be attended to is, that the outside shall be uninsulated. A Jar, while charging, will sometimes discharge itself spontaneously. This effect will be more likely to happen, if the uncoated interval is very clean and dry, and may be prevented altogether, by previously breathing on the uncoated part.†

(2.) *The opposite sides of a charged Jar, are in different electrical states, the one positive and the other negative.* Thus, if a pith ball, suspended by a silk thread, be applied to the knob, it will first be attracted to it, and then repelled; but it will now be attracted by the outside coating, until it becomes electrified in the same way, and then repelled, and so on.

(3.) *In order to receive the charge, the outside of the Jar must be uninsulated.* If we attach a string to the knob of the Jar, and suspend it, in the air, to the prime conductor, and put the machine in operation, no charge will be communicated to the Jar. The same result will follow, if the Jar stands on an insulating stand,‡ or is in-

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* Priestley's Hist. Elec. p. 84. † Singer, El. Elec. p. 101.

‡ An insulating stand, is any flat support, insulated by a pillar of glass. The pillar is usually a solid cylinder of glass, from six to twelve inches long, varnished so as to protect it from moisture. A junk bottle, surmounted by a circular piece of wood dry and varnished, makes a very good insulating support.

sulated by any other method. An insulated Jar, however, may be charged by connecting its knob with the positive conductor, and its outer coating with the rubber.*

(4.) *A second Jar may be charged, by communication with the outside of the first, while the latter is receiving its charge.* The charge communicated to the second Jar, is of the same kind as that of the first, and nearly of the same degree of intensity, provided the capacity of the two Jars be the same. Moreover, if a third, a fourth, or any number of Jars, of the same size, be connected, in a similar manner, with each other; namely, having the knob of each in communication with the outside coating of the next preceding,—then all the Jars will be charged with the same kind of electricity, but the degree of intensity will decline a little in the successive Jars. If the charge be derived, through the prime conductor, from the cylinder or plate, as is usually the case, it will be the positive or vitreous electricity.

(5.) *A Jar may be charged negatively, by receiving the electricity of the rubber*,—the rubber being insulated, and the prime conductor uninsulated. For this purpose, the chain usually attached to the rubber may be transferred to the prime conductor.

(6.) *When two Jars are charged, the one positively and the other negatively, on forming a communication between the insides of both, by connecting the two knobs, no discharge will take place, unless the outsides be in conducting communication.* Thus, if two Jars be charged, the one from the prime conductor and the other from the rubber,† and placed at the distance of a few inches from each other, on insulated supports, on connecting the two knobs by the discharging rod, no discharge will follow; but, let a wire be laid across the supports, touching the outside of each Jar; then, on applying the discharging rod to the two knobs, an explosion will immediately ensue.

By means of two Jars differently charged, and placed as above, with their outsides in conducting communication, the experiment

* Singer, Elem. Elec. p. 106.

† And both may be thus charged at the same time, by connecting one with the insulated rubber, and the other with the insulated prime conductor, the Jars themselves being uninsulated.

may be exhibited, which is called the *Electrical Spider.* It consists of a small piece of cork, so fashioned as to represent the body of a spider, and blackened with ink, having a number of black linen threads drawn through it to represent the legs. This is suspended by a silk thread, half way between the knobs of the two Jars, and vibrates for a long time from one knob to the other, until both Jars are discharged. The rationale will be obvious on a little reflection.

(7.) *The charge of any Jar may be divided into definite parts;* that is, the half, the fourth, or any aliquot part of the charge may be taken.* This may be done by connecting the inner and outer coating of the charged jar, with the inner and outer coating of an unelectrified jar, of the same size and thickness. The respective charges will be measured by the quadrant electrometer,† (Fig. 121.)

(8.) *The electricity is accumulated on the surface of the glass, and the coatings serve merely as conductors of the charge.* This is proved by the fact, that when the coatings are movable, so that they can be taken off from the jar after it is charged, neither of them exhibits the least sign of electricity; while if another pair of coatings is substituted, which have not been electrified, on forming the communication between the inside and outside, the usual discharge takes place, showing that the whole of the charge was retained on the glass surfaces of the jar.‡

(9.) *The charge of a Leyden Jar may be retained for a long time.* If the surfaces are well separated from each other, the charge remains for many days or even weeks. The charge is usually dissipated by the motion of particles of dust, or other conducting substances in the atmosphere, from one of the coatings to the other, or by the uncoated interval becoming moist, and losing its insulating power; consequently a jar will retain its charge longer in dry than in damp weather. Covering the uncoated part of the jar with melted sealing wax or varnish, prevents the deposition of moisture upon it, and consequently tends also materially to prevent the dissipation of its charge.§

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* Singer, p. 110.

† It is essential, however, that the electrometer should be graduated not by equal decisions, but according to a scale of arcs, the tangents of which are in arithmetical progression.

‡ Singer, p. 112. § Ib. 116.

(10.) *A pane of glass, a plate of air, or any other similar electric, may be charged to a greater or less degree in a manner analogous to that of the Leyden Jar.*—If a pane of glass is coated on both sides with a sheet of tin foil, leaving an uncoated interval all round the edges for the space of two inches;—and if we then hold the pane by one corner and apply the knuckle to the outer coating, and bring the inner coating to the prime conductor, the pane will be charged, and may be discharged, by applying the knobs of the discharging rod to the opposite metallic coatings. A plate of air may be charged in the same manner as a plate of glass; but as air is more readily displaced by electricity, in consequence of the mobility of its particles, a thicker stratum of it must be employed. The usual form of the experiment is to employ two circular disks of wood covered with tin foil, and well rounded at the edges, having a diameter of from two to four feet. One of the boards is to be placed flat upon a table, and the other being suspended by a silk cord from the ceiling, is adjusted so as to hang parallel over its surface, and at the distance of an inch or an inch and a half from it. The upper insulated board being connected with an electrical machine, the stratum of air between the boards becomes charged, and will communicate a shock if the upper and lower one be touched at the same time with opposite hands. The shock produced in this way is considerably less violent than that from an equal surface of coated glass; for the distance of the coatings is of necessity much greater, and the medium between them less perfectly insulating; and this last circumstance operates so rapidly when the charge is high, that its maximum of effect cannot be obtained but by making the discharge while the machine is in action. If the discharge is not made, spontaneous explosions from one disk to the other, through the intervening plate of air, will occur at intervals, as long as the electrization of the upper disk is continued.

(11.) If a coated pane of glass be held vertically, with two of its edges parallel with the horizon, and to the upper edges of the metallic coating two threads be attached directly opposite to each other; on communicating a spark to one of the coatings, the two threads both rise forming equal angles with the surface of the glass. On applying a conductor, as the finger, to one of the coatings the thread on that side immediately falls, while the other thread doubles its

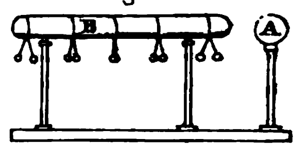
angle of elevation; so that the angles intercepted between the two threads, is a constant quantity.*

713. Before the learner is qualified to understand the explanation of the foregoing experiments, he must become more fully acquainted with the law of Induction (Art. 685.) upon which the theory of the Leyden Jar depends.

Law of Induction.†

Active electricity existing in any substance, tends always to induce the opposite electrical state in the bodies that are near to it. It is our object in this section to exhibit this important principle more fully than has yet been done in the preceding pages.

Fig. 128.



Let A (fig. 128.) represent an electrified glass globe, and B a metallic cylinder placed on insulating supports, near to the glass globe, but not near enough for a spark to pass. To the cylinder, let five pairs of pith balls be suspended, by conducting threads, viz. one pair near each end, one near the center, and one about half way between the center and either extremity. We shall find that every pair of pith balls, except those situated at a particular part of the cylinder not far from the center, will immediately diverge, indicating the electrical state of the part from which they are suspended. Those at either extremity diverge most; and the divergence diminishes as we approach the central parts to a certain point, where the pith balls suffer no effect, and where, consequently, the body is in its natural state. By means of the electrometer (Art. 120.) we may ascertain that the species of electricity is negative, or opposite to that of the glass globe in all those parts of the cylinder which are nearer to the globe than the before mentioned neutral point; and that it is positive in all parts of the cylinder more distant than this point. We may ascertain with much greater accuracy these electrical states by the employment of the proof plane and electrometer of Coulomb, (Art. 672.) than by pith

*Encyc. Metropol. Elec. p. 92.

† Biot, Précis Elém. tome I. or Library of Useful Knowledge, Art. *Electricity*.

balls; and the results are then found to correspond with the results of theory to be stated hereafter.

714. These effects, it should be remarked, are simply the result of electrical action at a distance; for they depend upon no other circumstance. They take place in an equal degree whatever substance is interposed between the bodies which are exerting this action on one another, provided the interposed substance undergoes no change in its own electrical state; a condition which is fulfilled in electrics, or non conducting bodies only. Thus induction will take place just as effectually through a plate of glass, as if no such substance had intervened.

Let us now suppose that the acting body A is not glass, or any electric, but a conducting body, a sphere of copper for example, charged with positive electricity, and insulated on a glass support. The primary effects of this sphere on the cylinder will be the same as in the former case; but the electrical state which the cylinder has acquired at the end adjacent to the globe, will *react* upon the electricity of the globe, tending to put it into a state still farther opposite to its own, that is, to render the nearer parts of the globe positive in a higher degree than they were before. This can be done only at the expense of the other side of the globe, which thus becomes less positive than before. But this new distribution of the electric fluid in the globe, by increasing the positive state of the side next to the cylinder, tends to augment its inductive influence upon the fluid in the cylinder; that is, to drive out an additional quantity of the fluid from the negative to the positive end. This is followed in its turn by a corresponding reaction on the globe, and so on, constituting a series of smaller adjustments, until a perfect equilibrium is established in every part. When this has been attained, the electrical states will, it is evident, be of the same kind as those consequent upon the *immediate* actions, though somewhat increased in intensity by the series of reactions.

715. The following experiment is a practical illustration of the preceding remarks. Furnish the copper globe with a pair of pith balls on each of two opposite sides. When the globe is insulated and alone, any electricity communicated to it, will diffuse itself equal-

ly over the surface, and both pairs of balls will diverge equally. But on bringing near to it a conducting body, the balls on the remoter side will immediately begin to collapse, while those at the nearer side diverge to a greater degree than before; thus showing the nature of the reflex operation of the induced electricity of the conductor, upon the body from which the induction originated.

It should be recollected, that in all the changes we have thus traced as the effects of induction, there has been no *transfer* of electricity from either of the bodies to the other; as might be inferred from their taking place equally well when a plate of glass is interposed. Another proof is afforded by the circumstance, that the mere removal of the bodies to a distance from one another, is sufficient to restore each of them to its original state. The globe remains as positively electrified as before; the cylinder returns to its condition of perfect neutrality; nothing has been lost and nothing gained on either side. The experiment may be repeated as often as we please, without any variation of the phenomena. But this would not be the case if the cylinder were divided in the middle, and one or both of the parts were removed separately, while they still remained under the influence of the globe. The return of the electric fluid from the positive to the negative end being thus prevented, each part will retain, after its separation, the electricity which had been induced upon it. The nearer portion will remain negative; the remoter portion positive. If the division had been in three parts, the middle part only would have been neutral. The experiment may be made by joining two or more conductors endwise, similar to B, Fig. 128, so that they may act as a single conductor when placed near to the electrified globe, and, after induction has thus been produced, removing them separately, and examining their electrical states. If the number of conductors be three, the first will be found negative the third positive, and the second neutral.

716. Another modification of effect will take place when an insulated conductor, rendered electrical at both ends by induction, is made to communicate with another insulated conductor. Let us first suppose that a long metallic conductor is brought into contact with the remote end of the first cylinder B, Fig. 128, which has been rendered positive by induction. The fluid accumulated at this end will

now pass into the conductor, and will remove to the most distant part of it. The transit will take place before actual contact, and will be manifested by the appearance of a spark, when the bodies are brought within the striking distance. The removal of this portion of fluid to a greater distance, will occasion a disturbance in the equilibrium that had before been established. The repulsion which that fluid had excited, and which had contributed to prevent any more fluid from being propelled from the negative end, is now considerably weakened by the greater distance at which it acts; and more fluid will leave the negative end, which end will consequently become more highly negative. This change of distribution will again occasion a further effect by its reaction on the fluid in the globe whence the action originally proceeded; and another series of changes and adjustments will follow, until a new condition of equilibrium takes place, and then the fluid will be at rest.

717. Thus we learn that the effects of induction in a conductor are augmented by increasing its length; they would, therefore, be greatest of all, if we could give it infinite length: but the same condition is attainable by placing the conductor in communication with the earth, which will carry off all the fluid which the electrified body is capable of expelling from the nearest end. Accordingly, if we touch with the finger, or with a metallic rod held in the hand, the remote end of an insulated conductor under the influence of induction, we obtain a spark more or less vivid according to the intensity of the electricity so induced; and the conductor so touched has now only one kind of electricity, namely, the one opposite to that of the electrified body which is acting upon it. The part touched is brought into a state, in which it appears to be neutral, as long as it remains in the vicinity of the electrified body; because the actions of the redundant fluid, and unsaturated matter in the two bodies, exactly balance one another. But it all the while really contains less fluid than its natural share, in consequence of the repulsive tendency of the fluid in the body which produces the induction; and this negative state will readily become active, if the conductor that has been touched be again insulated, and then removed from the influence of the former. This peculiar condition of a body, in which its parts are really undercharged or overcharged with fluid, although, from the

action of electrical forces derived from bodies in its vicinity, a state of equilibrium is established, and no visible effect results, has been denominated by Biot *disguised electricity.*

718. We have hitherto supposed the acting body to be positively electrified; but precisely the same effects would happen with regard to degree, although opposite as to the species of electricity, if it had been negatively electrified: and the same explanations will in every respect apply, with the requisite substitution of the terms negative for positive, and of attraction for repulsion, and *vice versa.* A little reflection will also show the application of the theory of double electricities to explain the same phenomena. Calling the electricity of the globe *vitreous* instead of positive, and substituting the term *resinous* for negative, we then say that the vitreous electricity of the globe drives off the similar electricity from the contiguous end of the cylinder, and attracts to it the resinous fluid. This again attracts the vitreous fluid from the remoter parts of the globe to the nearer surface; and thus, the vitreous and resinous, instead of the positive and negative fluids act and re-act on each other.

719. Another consequence of the induction of electricity must not be overlooked, namely, that the bodies between which it takes place, necessarily attract one another: for the mutual action between the contiguous surfaces of the globe and the cylinder, (Fig. 128.) which are in opposite electrical states, exceeds that of the remoter surfaces of those two bodies which are in the same electrical state, because the latter surfaces are more distant from each other than the former, and the force of electrical action is inversely as the square of the distance. Hence the attractive force always exceeds the repulsive. We have already seen (Art. 685.) that this circumstance sufficiently explains the fact, that conducting bodies previously neutral, are attracted by electrified bodies. Another fact, which appears more singular, and which cannot be accounted for on any other principle, is also a direct consequence of the law of induction. If a small insulated body weakly electrified, be placed at a distance from another and larger body, more highly charged with the same species of electricity, it will, as usual, be repelled; but there is a certain distance, within which if it be brought, attraction will take place instead

of repulsion. This happens in consequence of the inductive influence producing so great a change in the distribution of electricity, as to give a preponderance to the attractive forces of the adjacent parts of the two bodies, over the repulsive forces that take place in the other parts, and which would have acted alone if the fluid had been immovable.

720. From the foregoing principles it will be easy to understand, how induction may operate through a succession of conductors, which are all of them insulated except the last; and which are separated from each other by distances greater than that at which a transfer of electricity would take place. If under such circumstances, the first be electrified, alternate states of opposite electricities will be produced in the two ends of each conductor in succession. In all the ends nearest the first body, the electricity will be of the opposite kind to that with which the first has been charged; in the other ends it will be of the same kind as that of the first body. The vicinity of these opposite electricities, will tend powerfully to retain them in that condition, and will diminish their electric action on surrounding bodies. A large portion of the electricities so arranged and retained, is, therefore, in the condition designated by the term *disguised* electricity.* (Art. 717.)

The principles of induction developed in the preceding articles, serve to explain a number of the most curious and intricate phenomena of electricity, among which are those of the Leyden Jar; to this instrument, therefore, let us now return.

Theory of the Leyden Jar.

721. Upon what principle does this instrument receive and retain such an accumulation of the electric fluid? The answer is, because *the two surfaces of the jar mutually augment each other's capacities, upon the principle of induction.* To trace the operation of this principle a little more particularly, let us observe what takes place while a jar is charging from the prime conductor of the electrical machine. And, first, suppose the jar is insulated: a spark passes to the inner

* Lib. of Use. Knowl. Art. *Electricity.*

surface, and electrifies it positively. The inner surface now stands in the same relation to the outer, that the globe in figure 128, stands to the cylinder; that is, it tends to drive off the electricity of the same kind, and, in the same proportion, to attract the electricity of the opposite kind. But as the fluid cannot escape from the outer surface, (the jar being insulated) it of course remains to oppose the farther accumulation of the similar fluid on the inner surface. But, secondly, suppose the jar uninsulated, its outer coating having free communication with the earth. A spark passes to the inside as before and electrifies, positively, the inner coating. This repels the similar electricity from the outer coating, and renders the outside negative. Being negative, it re-acts by induction, (as the nearer surface of cylinder, in Art. 713.) on the inside and attracts to it a still greater charge, which is supplied by the prime conductor. This additional charge acting in the same manner on the outside, renders it more highly negative than before, in consequence of which, it attracts to the inside, a still farther charge of electricity from the machine. This series of actions and re-actions between the two surfaces of the jar, proceeds, in a diminishing series, until each surface becomes too feeble to exert any further influence on the other, and the jar is then *charged*.

Substituting the terms vitreous and resinous, for positive and negative, as in Art. 718, we may easily make the foregoing explanation conform to the supposition of two fluids.

722. For the purpose of making the theory of the Leyden Jar familiar, we may now recur to the experiments mentioned in Art. 712, and attempt the explanation of them.

In the structure of the Jar, we recognise the operation of the principle of *induction*. Here, an unelectrified body (the outer surface) is brought very near to an electrified body, (the inner surface,) without the possibility of communicating with each other, on account of the non-conducting properties of the glass. The nearer the two surfaces can be brought to each other, the more powerful is the effect of induction, that effect being inversely as the square of the distance. Accordingly, the thinner the jar, the more powerful is the

charge it will receive; but the danger of breaking prevents our employing such as are very thin.*

To trace the process of charging a jar a little more minutely, let us suppose the jar connected with the prime conductor of an electrical machine, from which a spark is communicated to the inner coating. This, according to the principles of induction, expels a similar quantity of the same fluid from the opposite unelectrified surface, and renders that negative, in the same degree as the inside is positive. Being negative, it increases the attraction of the inner surface for the opposite species of fluid, and another spark is received, which again expels an additional quantity of the same species of fluid from the outside, and thus the two surfaces continue to act upon each other reciprocally, though with constantly diminishing power, until the jar is charged.

The reason also is plain, why the outside of the jar must be uninsulated; since it is only in such case, that the foregoing process of induction can take place; and we readily see why a series of jars may be charged, from the portion of electricity which is expelled from the outside of the first jar.

723. When a jar is charged negatively from the rubber, just the opposite process in all respects takes place, the outside becoming positive by induction, and re-acting upon the inside. The case mentioned in Art. 712, (6.) where two jars differently charged, cannot be discharged except their outer surfaces be in conducting communication, will be readily understood; for it is impossible for the equilibrium to be restored by the union of the electricities on the inside, while the outside remains electrified. If we could suppose this to take place for a moment, and the electricity within to be restored to its natural state, it would again be immediately decomposed by the inductive influence of the electrified coating without.

724. The phenomena of the Leyden Jar, may be equally well explained, by substituting the terms vitreous and resinous, instead of

* The writer of this Treatise, had a large jar constructed of very thin glass: it took an extraordinary charge, and when discharged gave a report like that of an ordinary Battery; but it was fractured by the first experiment.

positive and negative, on the supposition of two fluids, since the principles of induction apply equally well to both hypotheses. Thus, it is as easy to suppose that the resinous electricity is induced upon the outside by the attraction of the vitreous electricity within, as it is to suppose that the outside becomes negative by the loss of a portion of its natural share; and the necessity of the outer surface being uninsulated, is as apparent in the one case as in the other. But we reserve the discussion of the comparative merits of these remarkable hypotheses, until the learner shall have become familiar with a great variety of electrical phenomena.

The Electrophorus and Condenser.

725. The ELECTROPHORUS is an instrument, which has the singular property of affording an indefinite quantity of electricity, for the charging of a jar, or for any other purpose, while it is itself charged only in a slight degree, and yet suffers no loss in consequence of what it imparts. According to the principles of Induction, whenever an uninsulated body falls under the influence of a body which is electrified and insulated, it is put into the opposite state of electricity, as is the case with the outside of a Leyden Jar. Now, if we insulate the body while it is under this influence, and then remove it from the sphere of influence, it will still retain the portion of electricity which was *induced* upon it; and, since an electrified body does not lose any portion of electricity by the influence it exerts on unelectrified bodies, on the principle of induction, it is plain, that by this means we may derive an indefinite quantity of the fluid from an excited body, and transfer it to a jar, without diminishing the degree of excitement in that body.

726. The construction of the Electrophorus is as follows. A round metallic plate (A) called the *sole*, (usually of brass,) is placed on an insulating support. A similar plate (B) furnished with a glass handle, is called the *cover*. A thin cake of resin,* of the same figure and

* Made by melting together equal weights of shell lac, resin and Venice turpentine.

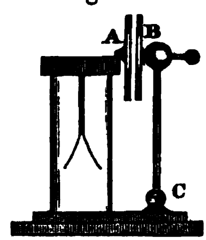
dimensions, is laid upon the sole. This cake being beaten with a furred surface, as a cat's skin, becomes charged with negative electricity. (Art. 677.) If we now bring near to it the cover, taking hold of the latter by the glass handle, the electricity of the metallic plate (B) has its equilibrium disturbed by the electrified body, which tends to expel its resinous and to attract its vitreous fluid. If therefore we give exit to the former, the plate will become positively electrified. This we may do by touching the plate (B) with the finger, while it is near the resinous cake; then on withdrawing the finger it will retain its charge, which may be transferred to the knob of a Leyden Jar, and the same process may be repeated any number of times, until the Jar becomes charged. By using a glass plate, instead of the cake of resin, we may obtain a similar charge of negative electricity, the species of fluid afforded by induction being always the opposite of that of the excited body.

The Electrophorus has been known to retain its power undiminished for months, and may therefore be regarded as a sort of magazine of electricity.

727. The Condenser is an instrument designed to collect very feeble degrees of electricity, (feeble in consequence of being spread over a large surface,) and so to *condense* it into a small compass as to render it sensible. It depends, like the Electrophorus and Leyden Jar, wholly on the principle of Induction.

One out of the numerous forms of instruments of this description, will serve as an illustration of the principle: the utility of these ingenious contrivances for operating on weak portions of electricity, has been very much diminished in consequence of the wonderful sensibility of the Torsion Balance.

Fig. 129.



728. To the metallic cover of a gold leaf electrometer, is attached a small disk of metal A, and on an insulating support, at a small distance from the electrometer, is placed a similar metallic disk B. The glass support BC has a joint at C, by means of which the disk B may be turned away from the disk A, or brought close to it, at pleasure. Let the substance whose

electricity is to be rendered sensible by the Condenser, be placed in contact with the cover of the Electrometer, and of course in communication with the plate A. Now, were not the fluid in the given body in a very weak state, it would be manifested by the divergence of the gold leaves; but, by the supposition, it is in too weak a state to produce any effect on them. But on bringing the plate B close to A, and touching it with the finger, the series of actions and reactions, explained in Articles 713, 714, &c. commences between the two plates, in consequence of which the capacity of each is greatly augmented. Then, on withdrawing again the plate B and discharging its electricity, it is brought anew to the vicinity of A, to be acted upon still more powerfully, in consequence of the electricity which it had previously acquired, and to act upon A, reciprocally, with greater energy than before. After repeating this process a great number of times, and finally separating the two disks, the gold leaves will diverge to a greater or less distance, according to the amount of fluid accumulated.

As the power of Induction is inversely as the square of the distance of the two bodies under its influence, it is desirable to bring the plates as near to one another as possible, without suffering a spark to pass. The plates, therefore, are sometimes covered with a coat of varnish, or protected by a very thin plate of glass.

CHAPTER IV.

OF ELECTRICAL LIGHT.

729. Light, we have seen, is not a constant attendant of electrical phenomena. Indeed, until noticed by Otto Guericke, it was not known to have any relation to electricity.

Electrical light appears whenever the fluid is discharged, in considerable quantity, through a resisting medium.

Accordingly, no light is perceived when electricity flows freely through good conductors; but if such conductors suffer any interruption, as by the intervention of a space of air, or even of an imperfect conductor, then the attendant light becomes manifest.

730. We shall best learn the properties of the electrical spark, by attending to a variety of experiments in which it is exhibited.*

A glass tube rubbed with black silk, which has been smeared with a little electrical amalgam, will yield copious sparks and flashes of light. The tube should be warm, dry, and smooth, and of a size not less than two feet in length, and three fourths of an inch in diameter.

The electrical machine, when in vigorous action, affords brilliant circles and streams of light. In order to render the light afforded by turning the machine abundant, several practical expedients are necessary. All parts of the machine must be dry and warm, (but not hot.) It is useful to rub very freely the glass plate or cylinder, with an old silk handkerchief. Black spots or lines that collect on the glass, especially when the amalgam is new, are to be carefully rubbed off, and should dust or down collect on the amalgam of the rubber, this must be removed. The action of the cylinder will be increased by the following process: smear the bottom of the cylinder with a thin coat of tallow; then turn the machine until the tallow is all taken up by the rubber and flap. The pores of the flap will then become filled with tallow, it will apply itself more closely to the cylinder, and the supply of electricity will become more copious. A convenient method of recruiting the action of the machine, is to coat a circular disk of paste board or leather with amalgam, and to apply it to the glass plate or cylinder while the machine is turning.

If the chain be removed from the rubber to the prime conductor, so that the former shall be insulated and the latter uninsulated, on bringing the ends of the fingers near the rubber, a stream of diluted light will pass between the fingers and the rubber.

731. *The length, color, and form of the electric spark, varies with the nature of the conductors between which it passes, and with that of the medium interposed between them.*

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* In experiments on electrical light, the room is supposed to be dark. They appear to best advantage in the night.

Electrical sparks are more brilliant in proportion as the substances between which they occur are better conductors. A spark received from the prime conductor upon a large metallic ball, is short, straight, and white; on a small ball it is longer, and zigzag; received on the knuckle, a less perfect conductor, it is purplish or reddish; on wood, or ice, or a wet plant, or water, it is red. Moreover, a longer spark can be obtained from a small ball, attached to the prime conductor by a wire five or six inches long, than from the prime conductor itself; and the longest, and most zigzag spark is obtained when the knob of a Leyden Jar is presented to a similar brass ball attached to the prime conductor. From a point positively electrified, the fluid passes in the form of a brush or pencil of rays; a point connected with the negative side, exhibits a luminous star.

A metallic chain connected with the prime conductor, becomes illuminated at the points where two links join, and at other points where the conducting powers of the metal are impaired by rust, or where roughnesses occur. If the chain have been previously corroded, artificially, by dipping it into a solution of salt, or a strong acid, and suffering it to remain until the outside has become rusty, the experiment will be more striking. When the chain is so good a conductor as to afford a ready passage to the fluid, the light will be produced more abundantly if the remoter end of the chain be held by the discharging rod, so as to insulate it; or it may be attached to any other insulating support.

732. *The electric spark passes, with increased facility, through rarefied air; and the distance to which it will pass between two conductors, is augmented as the rarefaction is made more complete.*

Instead of the distance of five or six inches, which is the limit of the spark from the prime conductor of an ordinary machine in the open air, the spark will pass through the space of eighteen inches or more, in an exhausted receiver. If a pointed wire, terminating in a knob above, be introduced into the top of a tall receiver, and the receiver be placed on the plate of the air pump, on connecting the knob of the wire with the prime conductor, and turning the machine, a brush of light only will appear at the extremity of the wire; but, on exhausting the air, this brush will enlarge, varying its appearance and

becoming more diffused as the air becomes more rarefied, until at length the whole receiver is pervaded by a beautiful bluish light, changing its color with the intensity of the transmitted electricity, and producing an effect which with an air pump of considerable power, is pleasing in the highest degree.*

When a charged jar is placed under the receiver of an air pump, as the exhaustion proceeds, a luminous current flows over the edge of the jar from the positive to the negative side, until the equilibrium is restored.

733. Electric light exhibits a very beautiful appearance, as it passes or *flows*, through the *Torricellian Vacuum.* The color is of a very delicate bluish or purple tinge, and the light pervades the entire space. But the most pleasing exhibitions of this kind, are made by forming an artificial atmosphere of vapor in the Torricellian tube. Ether or alcohol, passes into the state of vapor, when the pressure of the atmosphere is removed; and accordingly, on introducing a drop of one of these fluids into the Torricellian vacuum, it immediately evaporates and fills the void. If, now, a strong spark be passed from the prime conductor through this vapor, the spark will exhibit various colors: in ether, it is an emerald green, or mingled red and green; in alcohol it is red or blue; but the colors vary somewhat with the distances at which they are seen.

734. Sir Humphry Davy performed a number of experiments, on the passage of electricity through a vacuum, of which an account is given in Philosophical Transactions for 1822. He succeeded in forming a Torricellian vacuum quite free from air, but in such cases, a small portion of the mercury itself is converted into vapor, and from this he could not free the empty space. In all cases when the mercurial vacuum was perfectly free from air, it was permeable to electricity, and was rendered luminous by either the common spark, or the shock from the Leyden Jar. But the degree of the intensity of this phenomenon depended upon the temperature. When the tube was very hot the electric light appeared in the vapor of a bright green color, and of great density. As the temperature diminished, it lost its viv-

* *Singer.*

idness, and when it was artificially cooled to 20° below zero, it was so faint as to be visible only in the dark. In all cases, where the minutest quantity of rarefied air was introduced into the mercurial vacuum, the electric light, changed from green to sea green, and by increasing the quantity of air, it changed to blue and purple. Also when the temperature was low, the vacuum became a much better conductor.

A more perfect vacuum was formed by means of melted metals, as tin, of a more fixed nature than mercury, and therefore not liable to impair the vacuum by vapor of their own. A vacuum being made by means of fused tin, the electric light at temperatures below zero, was yellow, and of the palest phosphorescent kind, requiring almost absolute darkness to be perceived; nor was it perceptibly increased by heat. When the temperature was diminished, the electrical light (transmitted through vapor of mercury) diminished also till the temperature was reduced to 20°; but between 20° and —20° it seemed stationary.

Unless the electrical machine was very active, no light was visible during the transmission of electricity; but that the electricity passed was evident, from the luminous appearance of the rarefied air, in other parts of the tube.

From these and various similar experiments related by Davy, it seems demonstrated, that electricity is capable of passing through a perfect vacuum, but that the light emitted depends upon the vapor or air through which it passes, and that if the vacuum were perfect, no light whatever would appear.*

In condensed air, on the contrary, the spark passes with greater difficulty than ordinary. In such case, also, its whiteness, and brilliancy are augmented, and its course is zigzag. These appearances are even exhibited by passing the spark through *confined* air, of only the ordinary density.

735. The colors of the spark, are pleasingly varied by passing it, in a condensed form, as in the Leyden Jar, through media of different kinds. The experiment is performed by making the given body

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* *Phil. Trans.* 1822, or *Thomson*, Outlines, p. 470.

form a part of the circuit of communication, between the inside and outside of the Leyden Jar. A ball of ivory in this situation exhibits a beautiful crimson; an egg, a similar color, but somewhat lighter; a lump of sugar, gives a very white light, which remains for some time after the spark has passed; and fluor spar exhibits an emerald green light, or, in some cases, a purple light, which also continues to glow in the dark for some seconds. The great intensity of the light is shown by the strong illumination which the sparks in the jar communicate to bodies slightly transparent. Thus an egg has its transparency greatly increased; and if the thumb be placed over the space which separates the two conducting wires that communicate with the two sides of the jar respectively, the illumination is so powerful, that the blood vessels and interior organization of the organ may be distinctly seen.

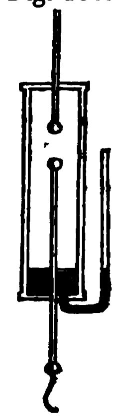
736. Metallic conductors, if of sufficient size, transmit electricity without any luminous appearance, provided they are perfectly continuous; but if they are separated in the slightest degree, a spark will occur at every separation. On this principle, various devices are formed, by pasting a narrow band of tin foil on glass, in the required form, and cutting it across with a pen knife, where we wish sparks to appear. If an interrupted conductor of this kind be pasted round a glass tube in a spiral direction, and one end of the tube be held in the hand, and the other be presented to an electrified conductor, a brilliant line of light surrounds the tube, which has been called the spiral tube, or diamond necklace. By enclosing the spiral tube in a larger cylinder of colored glass, the sapphire, topaz, emerald, and other gems may be imitated. Words, flowers, and other complicated forms, are also procured nearly in the same manner, by a proper disposition of an interrupted line of metal, on a flat piece of glass.

737. *The light of the electric spark, is not a constituent part of electricity, but arises from the sudden compression of the air, or other medium through which it passes.*

It is well known, that air is capable of affording a spark by sudden compression. There is a kind of match constructed on this principle, in which a small portion of air contained in a close cylinder, being suddenly compressed by forcing down a piston, yields a spark sufficient to light a quantity of tinder at the bottom of the cylinder.

Now it is found by actual experiment, that electricity has the power of condensing air. This fact is shown by means of a small instrument called *Kinnersley's Air Thermometer.* It consists of a glass tube, closed air tight at the two ends by brass caps, through each of which passes a movable wire, terminated within by a small ball. Through the lower cap is inserted a small glass tube open at both extremities, and turned upwards parallel to the cylinder. Into this tube is introduced a quantity of water sufficient to cover the bottom of the cylinder, and of course to rise a little way into the tube. The two balls being set at some distance from each other, and a spark from the Leyden Jar being passed between them, the air within is suddenly rarefied, and the water ascends in the tube, and again descends, when the explosion is over. This sudden rarefaction of a portion of air before the electric spark, must cause a sudden and powerful compression in the portions of air immediately adjacent. The immense velocity of the spark must greatly increase the resistance, and of course the force of compression. This appears to be an adequate cause for the production of the light that accompanies the electric discharge, and hence we conclude, that light is not inherent in the fluid itself. The greater density and brilliancy of the spark in condensed air, and its feebleness and diffuseness in a rarefied medium, are facts which accord well with the supposed origin; and the *zigzag* form of the spark when long, or when passing through condensed air, is well explained by the same theory. For the electric fluid in its passage through the air, condenses the air before it, and thus meets with a resistance which turns it off laterally; in this direction it is again condensed, and has its course again changed; and so on, until it reaches the conductor towards which it is aiming. The zigzag form of lightning is accounted for on this principle.*

Fig. 130.



Electrical light is found by optical experiments, to have precisely the same nature with the light of the sun, being like this resolved into various colors by the prism, and possessing other properties, to be described under the head of Optics, which identify it with solar light.

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* Biot, Traité de Phys. tome 2.—Encyc. Metropol. Art. *Electricity.*

CHAPTER V.

OF THE ELECTRIC BATTERY.—MECHANICAL AND CHEMICAL AGENCIES, AND MOTIONS OF ELECTRICITY.—EFFECTS OF ELECTRICITY ON ANIMALS.

738. *An electric battery consists of a number of Leyden jars so combined, that the whole may be either charged or discharged at once.*

Very large jars cannot be obtained; it is rare to find one more than two feet high, by one and a half in diameter. Yet some of the mechanical effects of electricity, to be described hereafter, require a much greater accumulation of the fluid than can be obtained from any single jar. The battery is constructed as follows. Large jars, twelve or fourteen inches high, by five or six inches in diameter, are coated like ordinary Leyden jars. Twelve of these constitute a battery sufficiently powerful for most purposes, but the power of the battery may be carried to an indefinite extent by increasing the number of jars. When the number is twelve, they are placed four in a row in a box, the bottom of which is coated with tin-foil, by means of which the outsides of the jars are all in conducting communication. Each jar is separated from the rest by a slight partition of wood. To connect the insides of the jars, their knobs are joined by large brass wires. It is obvious, therefore, that the battery is equivalent to a single jar of enormous size, comprehending the same number of square feet.

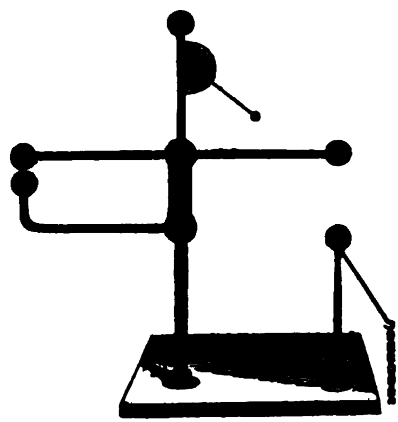
The object of the battery is to accumulate a great *quantity* of the electric fluid, which is in proportion to the extent of surface: the *intensity*, or elastic force, as indicated by the quadrant electrometer, is no greater in the battery when charged, than in a single charged jar. The battery, like the common jar, is charged by bringing the inside into communication with the prime conductor of an active and powerful electrical machine:* it is discharged, as usual, by forming

* As the process of charging a large battery is tedious and laborious, it has been proposed to charge each jar successively, after that

a connexion between the inside and outside, commonly by means of the discharging rod.

739. To measure the intensity of the electrical charge, an apparatus is employed called *Cuthberton's Balance Electrometer*, Fig. 131. It consists of a metal rod, about thirteen inches long, terminated by balls and balanced on a knife-edged center, in the manner of a scale beam. One arm of the balanced rod is graduated, and has a slider upon it, which, when placed at different distances from its fulcrum, loads the arm with a proportionate weight from one grain to sixty. The graduated end of the balance rests upon a similar brass ball, which is supported by a bent metal tube from the same insulating stand; and at four inches below the opposite extremity, another insulated ball is placed, which is to be connected with the outside of a jar or battery. Now if the metallic support of the balance be connected with the conductor, or the inner coating of the jar, and this last be electrified, there will be an attraction between the extremity of the balance and the lower insulated ball, because they are connected respectively with the opposite surfaces of the jar; and when the force of this attraction exceeds the weight with which the opposite arm is loaded, the attracted arm of the balance will descend, and discharge its electricity on the lower insulated ball. The power of the attraction is always proportioned to the intensity of the charge; and as, in this instrument, the attraction has to overcome a resistance proportioned to the weight with which the balance is loaded, that

Fig. 131.



which is immediately connected with the prime conductor, by means of the electricity expelled from the outside of the first, as is explained in article 712, (4.)—Encyc. Metrop. Art. *Electricity*.

weight becomes a proper comparative measure of the intensity of any required charge. The quadrant electrometer, attached to the top of the instrument, is useful to indicate the *progress* of the charge, as that is not shown by the action of the balance itself.*

Electrical batteries indicate only the *intensity* of the accumulated electricity, that is, its deviation from a state of natural distribution; the *quantity* can be inferred only from the comparative extent of the charged surface, or estimated by an examination of its effects, and is therefore by no means accurately appreciable.

The largest machine and battery hitherto constructed, were made for the Teylerian museum, at Haarlem. It consists of two circular plates of glass each five feet five inches in diameter. The prime conductor consists of several pieces, and is supported by three glass pillars, nearly five feet in length. The force of two men is required to work the machine; and when it is required to be put in action for any length of time, four are necessary.

At its first construction nine batteries were applied to it, each having fifteen jars, every one of which contained a square foot of coated glass; so that the grand battery, formed by the combination of all these, contained one hundred and thirty five feet. As examples of the great power of the Teylerian machine, we may mention the following: it charged a Leyden jar by turning the handle half round,—a charge which the jar would receive, and lose by discharging itself spontaneously, eighty times in a minute. A single spark from the conductor melted a considerable length of gold leaf. A spark, or zigzag stream of fire would dart from the prime conductor to a neighboring conductor to the distance of ten feet. A wire three eighths of an inch in diameter, was found to be insufficient to transmit the whole charge of the prime conductor, but the wire would give small sparks to a conductor brought near it. The sphere of influence (Art. 684.) extended to the distance of forty feet, so as sensibly to affect the pith ball electrometer. The *spider web* sensation (or that peculiar sensation resembling that of the spider's web) which is experienced by holding an excited glass tube to the face, was felt by bystanders to the distance of eight feet from the machine.*

* *Singer*, p. 137. † *Cavallo*, Complete Treatise, Vol. II.

Mechanical Effects of Electricity.

740. *The sound produced by an electric discharge, is ascribed to the sudden collapse of the air, which has been displaced by the passage of the electric fluid.*

Hence the sound is greater in proportion to the quantity and intensity of the charge. A battery, when fully charged, gives a loud explosion.

741. *Imperfectly conducting substances, through which a powerful electric charge is passed, are torn asunder with more or less violence.*

A large Leyden Jar is sufficient for exhibiting some of these mechanical effects: others require the power of the Battery. When the charge is passed through a thick card, or the cover of a book, a hole is torn through it, which presents the rough appearance of a bur on each side. By means of the Battery, a quire of strong paper may be perforated in the same manner; and such is the velocity with which the fluid moves, that if the paper be freely suspended, not the least motion is communicated to it.* (See Art. 264.) Pieces of hard wood, of loaf sugar, of stones, and many other brittle non-conductors, are broken or even torn asunder with violence, by a powerful charge from the battery. If two wires be introduced into a soft piece of pipe clay, and a strong charge be passed through them, the clay will be curiously expanded in the interval between the wires.

The expansion of *fluids* by electricity is very remarkable, and productive of some singular results. When the charge is strong, no glass vessel can resist the sudden impulse. Beccaria inserted a drop of water between two wires, in the center of a solid glass ball of two inches diameter; on passing a shock through the drop of water, the ball was dispersed with great violence. In like manner, by the sudden expansion of a small body of confined air, strongly electrified, explosions may be produced, and bodies that resist its expansion are

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* Singer.

projected with violence. Even good conductors, when minutely divided, are expanded by electricity. Thus, mercury, confined in a capillary glass tube, will be expanded with a force sufficient to splinter the tube.

Chemical Effects of Electricity.

742. ***By means of Electricity, more or less accumulated, a variety of chemical effects may be produced; such as the combustion of inflammable bodies, the oxidation, fusion, and even combustion of metals, the separation of compounds into their elements, or the union of elements into compounds.****

Ether and alcohol may be inflamed by passing the electric spark through them; nor is the effect diminished by communicating the spark by means of a piece of ice or any other cold medium. The finger may be conveniently employed to inflame these substances. Phosphorus, resin, and other solid combustible bodies, may be set on fire by the same means; gunpowder and the fulminating powders may be exploded; and a candle may be lighted. Gold leaf and fine iron wire may be burned, by a charge from the battery. Wires of lead, tin, zinc, iron, copper, platina, silver and gold, when subjected to the charge of a very large battery, burn with explosion and are converted into oxides.†

The same agent, moreover, is capable of reviving these oxides; that is, restoring them to the state of pure metals. By a similar contrariety of properties, water is decomposed into its gaseous elements, and the same elements are reunited to form water; and the constituent gases of atmospheric air are, by passing a great number of electric charges through a confined portion of air, converted into nitric acid.

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* The chemical agencies of electricity are much more powerful and extensive as exhibited by the Galvanic apparatus, than by the common Electrical Machine.

† Singer, p. 185.

Motions of the Electric Fluid.

743. *The velocity of the electric fluid is apparently instantaneous.* A circuit of four miles has been formed, by means of wire, between the inside and outside of a Leyden Jar, and no perceptible interval was occupied during the discharge. Analogy, however, would lead us to believe that Electricity, like light, is progressive in its motions, but that it moves with a velocity too great to be measured, except for intervals of immense extent.*

744. *The electric fluid, in its route, selects the best conductors.* The Leyden Jar may be discharged with a wire held in the hand, without the insulating handle used in the Discharging Rod; since metallic wire is a better conductor than the hand, and the fluid will take its route through that in preference to the hand. But if a wooden discharger be substituted for the wire, the shock will be felt, since animal substances are better conductors than wood. It is necessary to remark, however, that when the charge is very intense or the quantity great, as in the Battery, then some portion of the fluid will escape from the discharging wire and pass through the hand. In such cases, therefore, it is prudent to make use of the Discharging Rod.

Lightning, in striking a building, usually takes a course which indicates the preference of the fluid for the best conductors.

745. *The electric fluid will sometimes take a shorter route through a worse conductor, in preference to a longer route through a better conductor.* The spark will pass through a short space of air, instead of following a small wire thirty or forty feet.† The preference of

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* The velocity of light appears to be instantaneous, for such distances as four miles; but when such intervals are taken as the diameter of the earth's orbit, light is found to have a progressive velocity of 192,500 miles per second. If, therefore, electricity actually moves with a progressive velocity like that of light, still the time occupied in traversing the space of four miles would be inappreciable, since it would equal only about $\frac{1}{50000}$ part of a second.

† Singer.

the shorter route is sometimes indicated in taking the electric shock. While one person is receiving the shock from the Leyden Jar, another may grasp his arm without feeling the least effect from the charge.

746. *The course of the charge is frequently determined by the influence of points, either in dissipating or in receiving the fluid.* Sharp points connected with the best conductors, greatly favor the dispersion of the fluid during its passage, and sharp pointed conductors draw the charge towards them, from a great distance around. The finest needle, held in the hand towards the knob of one of the jars of a charged Battery, will silently discharge it, in a few seconds; and if we apply one hand to the outside of a Leyden Jar, and with the other bring a fine needle to the knob of the Jar, only a comparatively feeble shock will be felt, the charge being rapidly dissipated while the needle is approaching the knob.

Effects of Electricity upon Animals.

747. We have already several times incidentally adverted to the shock communicated to the animal system, when it is brought into the electric circuit, so that the charge passes through it. We now propose to consider this interesting part of the subject more particularly.

748. *The Electric Shock is received, whenever the animal system is made a part of the conducting communication, between the inside and outside of a charged Leyden Jar.* A convenient method of administering the shock, is to place the charged jar on a table, resting immediately on a metallic plate,* as a plate of tin, lead, or copper; then grasping a metallic rod in each hand, touch one of them to the plate and the other to the knob of the Jar, and a sudden convulsion of the limbs or the breast will be experienced, more or less violent according to the strength of the charge. The effect is greatly height-

* It is safer to employ such a plate than to bring the conducting rod immediately into contact with the outside coating of the Jar; for, in such case, persons unaccustomed to receive the shock, are apt to overturn the Jar and break it.

ened by feelings of dread or apprehension, and it may be resisted to a considerable degree by a voluntary effort. A slight charge affects only the fingers or the wrists; a stronger charge convulses the large muscles above the arm-pits; a still greater charge passes through the breast and becomes in some degree painful. Electricians, however, have frequently adventured upon charges sufficiently powerful to convulse the whole frame.

749. *The shock may be communicated to any number of persons at once.* This is usually effected by their joining hands, while the first in the series holds one of the metallic rods, (Art. 748.) with which he touches the plate or outside of the jar, and the last in the series holds the other rod, with which he touches the knob of the Jar, at which instant the whole number receive the shock at the same moment, and that however extensive the circle of persons may be. The Abbe Nollet, a celebrated French electrician, gave the shock, at once, to one hundred and eighty of the king's guards, and to all the members of a convent, (who formed a large community.) All gave a spring, at the same moment.* The strength of the shock, however, is somewhat diminished by passing through a long circuit, some portion of the fluid being dissipated on the way. The connexion, instead of being made by taking hold of hands, may be formed between any number of persons A, B, C, D, &c. as follows: A may touch his foot to the foot of B; B may take the hand of C, who may touch the foot of D; then each of the company will feel the shock in one arm and one leg, showing that the fluid pursues the most direct course, agreeably to Art. 745.

750. If the discharge from two square feet of coated surface be made to pass through the region of the diaphragm, a sudden convulsive action of the lungs produces a loud shout. A smaller charge produces a violent fit of laughter, even in the gravest persons. A very strong charge, passed through the diaphragm, produces involuntary sighing and tears, and sometimes brings on a fainting fit.† The charge of a large battery is sufficient to destroy human life, especially if it be received through the head. By standing on the *Insulating Stool*, which is a stool with glass feet, a person becomes an insulated

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* Priestley, p. 97.

† Encyc. Metrop.—Morgan's Lectures.—Singer's Elements.

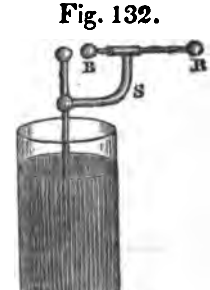
conductor, and may be electrified like any other insulated conductor. A communication being made with the Machine, the fluid pervades the system, but excites hardly any sensation except a prickling of the hair, which at the same time rises and stands erect; for the hairs, being similarly electrified, mutually repel each other.

751. While in this situation, the human system exhibits the same phenomena as the prime conductor when charged; that is, it attracts light bodies, gives a spark to conductors brought near it, and communicates a slight shock to another person who receives the spark from it. Indeed, the same shock is felt by both parties.

By means of the insulating stool, the most delicate shocks may be given; for the charge may be drawn off from any part, by imperfect conductors. Thus, a pointed piece of wood will draw off the charge from the eye, in a manner so gentle, as to secure that tender organ against any possibility of injury. By a variety of conductors, of different powers, and by points and balls, the sensations may be accommodated, with much delicacy, to the state of the patient, or to the nature of the affected part.

752. The shock may be communicated directly to any individual part of the system, without affecting the other parts, by making that part form a portion of the electric circuit, between the inside and outside of a Leyden Jar. Thus, let it be required to electrify an arm. Two *directors*, (consisting of wires terminating in brass knobs, and insulated by glass handles,) are connected by chains with the knob, and the outside coating of a charged Jar; then on applying one of the directors to the hand, and the other to the naked shoulder, the arm is convulsed. In cases where the patient requires only a moderate shock, the charge is regulated by a contrivance attached to the Jar called *Lane's Discharging Electrometer*, represented in Fig. 132. S is a stick of solid glass; B, R, two brass knobs, connected by a wire, which slides back and forth in such a way that it may be set at any required distance from the knob of the Jar. If the ball B be set in contact with the knob, then on touching the ball and the outer coating of the Jar, the entire charge of the Jar is received; but by removing the ball B from the knob, the half,

Fig. 132.



fourth, or any aliquot part of the charge, may be taken at first, and afterwards the remainder may be taken by sliding the wire nearer to the Jar.

753. It has already been mentioned, that life may be destroyed by strong electrical charges. Experiments have been made with the view of investigating the nature of this destructive action. Dr. Van Marum of Haarlem, selected for this purpose eels, which, as is well known, retain signs of irritability when cut into three, four or six parts, and even when deprived of their heads. The eels employed in these experiments, were a foot and a half in length, and the shock was conveyed through the whole body. They were instantly killed, and never moved afterwards. They were immediately skinned, and trial was made by pinching, pricking, &c. but no traces of irritability remained. When the shock was made to pass through individual parts, for example the head, these alone lost their irritability, while the rest retained it. When the head was kept free from the shock, the remaining parts only were paralyzed.*

It had been remarked that whenever animals had been killed by lightning, the process of spontaneous putrefaction ensued with unusual rapidity. This subject was examined by M. Achard of Berlin, by numerous experiments. From these it appeared that electricity accelerates putrefaction, since it was found that animals recently killed, and animal substances, such as raw beef, became putrid much sooner when electrified. General credit is given to the foregoing experiments, but it seems easy to account for the increased tendency of milk to sour, and of meat to become putrid, during a thunder storm, from the effects of heat and moisture, which are known and adequate causes of these phenomena.

754. Soon after the discovery of the Leyden Jar, commenced the application of Electricity to *Medicine;* and Medical Electricity, became thenceforth a distinct branch of the science. The first cure said to have been effected by this agent, was upon a paralytic. Electricity shortly became very celebrated for the cure of this disorder, and patients flocked in great numbers to the practitioners of

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* Nicholson's Jour. 8. 319—Encyc. Metrop. Art. *Electricity.*

this branch of the profession. As usual, the effects of this new remedy were greatly exaggerated, and it was widely extolled, not only for the cure of palsy, but of all other diseases.* It was even pretended that the virtues of the most valuable medicines might be transferred into the system through the medium of electricity, preserving their specific properties in the same manner as when taken by way of the stomach. Preparations of this kind were called *Medicated Tubes*. Pavati, an Italian, and Winkler, a German, were especially celebrated for this species of practice. The mode was to enclose the medicines in a glass tube, then to excite the tube, and with it to electrify the patient. In this way, it was said, the healing virtues of the medicines were communicated to the system in a manner at once efficacious and agreeable.†

755. Pretensions so extravagant could not long be sustained, and the natural consequence was that the use of electricity in medicine soon fell into great neglect, and has remained in this situation to the present time. There are however, certain properties inherent in this agent, which deserve the attention of the enlightened physician, and inspire the hope that, in judicious hands, it may still be auxiliary to the healing art. First, the great activity of this agent, particularly the facility and energy with which it can be made to act upon the nervous system, indicate that it has naturally important relations to medicine. The power of being applied, locally, to any part of the system, render it a convenient application in cases where other local remedies cannot be administered. Secondly, the acknowledged property of electricity to promote the circulation of fluids through capillary tubes, Art. 691. (7.) suggests the probability of its being efficacious in promoting the circulation of the fluids of the animal system, and in increasing the quantity of insensible perspiration. Thirdly, in the history of medical electricity are recorded well attested cures, effected by means of electricity, of such diseases as palsy, rheumatism, gout, indolent tumors, deafness, and a variety of other disorders.‡

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* Priestley, p. 409. † Priestley, 146.

‡ See Priestley's History of Electricity, pp. 146 and 406—Singer's Elements, p. 292—Phil. Transactions, *passim*—Encyc. Metropolitana, Elec. 105—Cavallo, *Complete Treatise*, Vol. 2.

CHAPTER VI.

OF THE CAUSE OF ELECTRICAL PHENOMENA.

756. For the sake of convenience, and for the purpose of avoiding repetition and circumlocution, we have made occasional use of the phrase *electric fluid*. It may be proper now to inquire whether there are any just grounds for supposing such a fluid or fluids to be present in electrical phenomena.

There are two modes by which the existence of such a fluid may be rendered probable: the first is, by showing that such a supposition is conformable to the analogy of nature; the second is, by proving that the agent of electrical phenomena exhibits the properties of a fluid.

757. First, *there are some reasons derived from analogy for believing in the existence of an electric fluid.* (1.) The reasons in favor of supposing that light and heat are caused by the agency of peculiar fluids, (arguments, however, that we cannot discuss here,) which have induced a general belief, are for the most part equally applicable to electricity. (2.) In the present state of our knowledge, the most subtile of all fluids, indeed the most attenuated form of matter, is hydrogen gas, of which one hundred cubic inches weigh only two and a quarter grains, which is nearly fourteen times lighter than common air. But at no distant period, means had not been devised by mankind for proving the materiality of common air, nor even of identifying the existence of the other gases, which now bear so conspicuous a part in experimental philosophy. But as knowledge and experimental researches have advanced, a series of fluids still more subtile than air, have come to light, until we have reached a body nearly fourteen times lighter than air, at which, at present, the series stops. Is it probable, however, that nature stops in her processes of attenuation precisely at the point where, for want of more delicate instruments, or more refined and powerful organs of sensation, our methods of investigation, and powers of discrimination come to their limit? An examination of the general analogies of nature, will lead us to think

otherwise. The subordination which exists among the different classes of bodies that compose the other departments of nature, is endless, or at least indefinite. In the animal creation, for example, beginning with the mammoth or the elephant, we descend through numerous tribes to the insect which is barely visible in the sunbeam. Before human ingenuity had devised means of aiding the powers of vision, the naturalist might have fixed this as the limit of the animal creation. But the invention of the microscope has carried the range of human vision immeasurably farther; and at each successive improvement in that instrument, new tribes of insects or animalcules have been revealed to the eye, still more and more attenuated. A similar subordination might be found in the vegetable kingdom, and in the organic structure of both animals and vegetables.

To apply this analogy to the case before us, we begin the series of inorganic bodies with platinum, and descend through classes of bodies constantly diminishing in density, until we come to ether, the lightest of liquids, and on the confines of those bodies which are invisible to the eye, and manifested only by the effects which they produce. By modern discoveries the series has been extended to hydrogen, a body two hundred and forty seven thousand times lighter than platinum. Here for the present we pause, standing in the same relation with respect to any fluids that may lie beyond, that the ancients stood with respect to common air, and all the other aëriform fluids.

Considerations of this nature lead us to believe that there are, in nature, fluids more subtile than hydrogen; and, such being the fact, we can hardly resist the belief, that Heat, Light and Electricity, are bodies of this class,—bodies which make themselves known to us by the most palpable and energetic effects, although their own constitution is too subtile and refined for our organs to recognise, or our instruments to identify them as material.

758. Secondly, in addition to the foregoing presumptions, in favor of the supposition that electricity is a peculiar fluid, *it exhibits in itself the properties of a fluid.* The rapidity of its motions, the power of being accumulated, as in the Leyden Jar, its unequal distribution over the surfaces of bodies, (Art. 704.) its power of being confined to the surfaces of bodies by the pressure of the atmosphere, its attrac-

tions and repulsions, are severally properties which we can hardly ascribe to any thing else than an elastic fluid of the greatest tenuity.

But granting the presence of an elastic fluid in electrical phenomena, it remains to be determined whether, according to the hypothesis of Franklin, these phenomena are to be ascribed to the agency of a single fluid, or whether, according to that of Du Fay, they imply the existence of two distinct fluids. The numerous facts with which the learner has been made acquainted in the preceding pages, will fit him to appreciate the evidence offered in favor of or against these hypotheses respectively.

759. The principles of each hypothesis have been already explained, (see Art. 675.) and they have been rendered familiar by repeated application. It will be recollected, that they concur in supposing that all bodies are endued with a certain portion of electricity, called their *natural share*, in which the fluid, whether single or compound, is in a state of perfect equilibrium; and that, in the process of excitation, this equilibrium is destroyed. But here the two views begin to diverge: the one supposes that this equilibrium is destroyed in consequence of the separation of *two fluids*, which, like an acid and an alkali combining to form a neutral salt, exactly neutralize each other by mutual saturation, but which, when separated, exhibit their individual properties; the other, that the equilibrium is destroyed, like that of a portion of atmospheric air, by greater or less exhaustion on the one side, or condensation on the other. In the former case, moreover, the equilibrium is restored by the reunion of the two constituent fluids; in the latter, by the movement of the redundant portion to supply the deficient, as air rushes into the exhausted receiver of an air pump.

It is a remarkable fact, that nearly every electrical phenomenon, may be perfectly explained in accordance with either hypothesis; nor is it agreed, that an *experimentum crucis** has yet been found.†

* The "experimentum crucis," is a phrase introduced by Lord Bacon, implying a fact which can be explained on one of two opposite hypotheses, and not on the other. The figure is derived from a cross set up where two roads meet, to tell the traveller which road to take.

† Lib. Useful Knowl.

760. One of the latest advocates of the hypothesis of a single fluid is Mr. Singer,* an able practical electrician, and the most distinguished defender of the doctrine of two fluids is M. Biot.† In support of the former doctrine, are offered such arguments as the following. (1.) Its greater *simplicity*. It is supposed to be more conformable to the Newtonian rule of philosophizing, "to ascribe no more causes than are just sufficient to account for the phenomena." The known frugality of nature, in all her operations, might lead us to suppose, that she would not employ two agents to effect a given purpose, when a single agent would be competent to its production. This argument, however, cannot be applied, either where one cause is *not* sufficient to account for the phenomena, or where there is direct proof of the existence of more agents than one. (2.) The appearance of a *current*, circulating from the positive to the negative surface, analogous to the passage of air of greater density into a rarefied space. This point is much insisted on by Singer, and numerous examples are brought forward, where the progress of such a current is manifest to the senses. Thus, the flame of a candle, brought into the circuit between the inside and outside of a Leyden Jar, is, on the discharge of the Jar, bent towards the negative side; a pith ball, under similar circumstances, moves in the same direction; when a charged Jar is placed under the receiver of an air pump, and the air is exhausted, a luminous cloud flows from the positive to the negative side, in whichever way the Jar is electrified. None of these arguments, however, are found to be conclusive; for the mechanical effects, which are here ascribed to an elastic fluid, that is, the electric fluid, flowing towards the negative side, can all be accounted for, either upon the principles of attraction and repulsion, common to both hypotheses, or from the mechanical impulse of a current of air, which is known to be repelled from a point positively electrified. The electric spark passing instantaneously, or at least with a velocity entirely inappreciable, it is impossible to determine its direction.

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* Elements of Electricity and Electro-Chemistry, by George John Singer. London: 1814.

† Traité de Physique, tome II.

The fact that *bodies negatively electrified repel each other,* (Art. 676.) is a strong argument against the truth of the hypothesis under consideration. It is not difficult to conceive that a self repellent fluid should communicate the same property to two pith balls in which it resided; but that the mere *deficiency* of the fluid should produce the same effect is incredible. This fact drove Æpinus, (a celebrated German electrician, who brought this hypothesis to the test of mathematical demonstration,) to the necessity of supposing that *unelectrified matter is self repellent,*—a supposition which is not only destitute of proof, but which is inconsistent with the general laws of nature, from which it appears that attraction and not repulsion exists mutually between all kinds of bodies. In the distribution of electricity upon surfaces differing in shape and dimensions, the fluid is found to arrange itself in strict accordance with hydrostatic principles, and that too in bodies negatively as well as positively electrified. Now that the privation, or mere absence of a fluid, should exhibit such properties of a present fluid, is inconceivable.

761. In favor of the doctrine of two fluids the following arguments are urged. (1.) *Two opposite currents* are supposed to be sometimes indicated. Thus, (Art. 741.) a card perforated by a strong electric discharge, exhibits burs or protrusions on both sides. The appearance of the *electric spark*, passing between two knobs, is supposed by some writers to indicate the meeting of two fluids from opposite parts. When the spark is short, the whole distance between the two knobs through which it passes, is illuminated. But when the spark is long, those portions of it which are nearest to the knobs, are much brighter than the central portions. Near the knobs the color is white, but towards the center of the spark it is purplish. Indeed, if the spark is very long, the middle part of it is not illuminated at all, or only very slightly. Now this imperfectly illuminated part, is obviously the spot where the two electricities unite, and it is in consequence of this union, that the light is so imperfect.* (2.) The two electricities are characterized by *specific differences*. The light afforded by the vitreous surface is different from that of the resinous;

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* *Thomson.*

when the two opposite portions of the spark meet, as above, the place of meeting is only half the distance from the negative that it is from the positive side; the bur protruded from the card is larger in the direction of the vitreous than in that of the resinous fluid; and the two severally produce certain chemical effects in bodies which are peculiar to each. (3.) But the most conclusive argument in favor of two fluids, is the perfect manner in which this supposition accounts for the *distribution of electricity* on bodies of different dimensions. (See Arts. 700—706.) On the hypothesis, that electrified phenomena are owing to the agencies of *two fluids, both perfectly incompressible, the particles of which possess perfect mobility, and mutually repel each other, while they attract those of the opposite fluid, with forces varying in the inverse ratio of the squares of the distances,*—on this hypothesis, M. Poisson, a celebrated mathematician of France, applied the exhaustless resources of the calculus, to determine the various conditions which electricity would assume in distributing itself over spheres, spheroids, and bodies of various figures. The results at which he arrived were such as accord in a very remarkable degree with experiment, and leave little doubt that the hypothesis on which they were built must be true. Nor is any supposition involved in the hypothesis itself inconsistent with established facts. (4.) Finally, authority is, at the present day, almost wholly on the side of the doctrine of two fluids,—an opinion which has constantly gained new adherents with every new discovery in the science of electricity, particularly in the department of Galvanism.

CHAPTER VII.

OF ATMOSPHERICAL ELECTRICITY.—THUNDER STORMS.—LIGHTNING RODS.

762. Having learned the laws of electricity from a great variety of experiments, the student is now prepared to look upon the works of Nature, and to study the phenomena which the same agent produces there on a most extensive scale.

The atmosphere is always more or less electrified. This fact is ascertained by several different forms of apparatus. For the lower regions, it is sufficient to elevate a *metallic rod* a few feet in length, pointed at the top, and insulated at the bottom. With the lower extremity is connected an electrometer, which indicates the presence and intensity of the electricity. For experiments on the electricity of the upper regions, a kite is employed, not unlike a boy's kite, with the string of which is intertwined a fine metallic wire. The lower end of the string is insulated by fastening it to a support of glass, or by a cord of silk. But as experiments of this kind involve some personal hazard, we subjoin, from an excellent treatise on practical electricity,* a few directions for the construction of this apparatus.

763. An electric kite should be constructed in the most simple manner, for it is an apparatus very liable to be injured or lost; its size should be moderate, as there is not often sufficient wind to raise one that is very large, which is besides on several other accounts very troublesome to manage. An ordinary paper kite about four feet in height, and two feet wide, varnished with drying oil, to defend it from the rain, is sufficiently well adapted to this purpose. The string must be made with a thin copper or silver thread, (such as is used for gilt lace,) entwisted with the twine of which it is formed, through its whole length. When the kite is raised, the string is insulated by attaching to it a silk cord, whose opposite extremity may be fastened to a rail, or any fixed or heavy body. The end of the metallic string is to be connected with an insulated conductor, and at two inches from the extremity of this conductor, a brass ball, well connected with the ground, or the nearest water, is to be placed; so that when the electricity becomes sufficiently intense to pass an interval of two inches, it will be conducted safely away without injury to the experimenter, who should be cautious in such cases not to approach the insulated conductor; but if he has occasion to remove any apparatus to or from it, to do so by the aid of long insulating handles or forceps.†

764. A few facts may be mentioned to show the hazard attending this class of experiments. Cavallo, on one occasion, had raised a

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* Singer's Elements.

† Singer, p. 267.

kite, the string of which was insulated by silk laee. A cloud was over head, and the electricity began to be abundant with which he charged a pair of Leyden Jars. In order to prevent any accident which might arise from too great an accumulation of the fluid, he wished to take off the insulating silk and to connect the string immediately with the ground. For this purpose, he took hold of the string and detached it from its support. "While I effected this, (says he,) which took up less than half a minute of time, I received about a dozen or fifteen very strong shocks, which I felt all along my arms, in my breast, and legs; shaking me in such a manner, that I had hardly power enough to effect my purpose, and to warn the people in the room to keep their distance."* Professor Richman, of Petersburgh, a distinguished devotee of our science, fell a victim to his temerity. He had constructed an apparatus for observations on atmospherical electricity, which was entirely insulated, and had no contrivance for discharging it when electrified too strongly. On the 6th of August, 1753, he was examining the electricity of this apparatus, in company with a friend: while attending to an experiment, his head accidentally approached the insulated rod, when his attendant observed a globe of blue fire, as he called it, as big as his fist, jump from the rod to the head of the professor, which, at that instant, was about a foot from it. M. Richman was killed instantly: a red spot was left on his forehead, his shoe was burst open, and part of his waiscoat singed; his companion was benumbed, and rendered senseless for some time; the door case of the room was split, and the door torn off its hinges.

765. The most powerful apparatus ever employed for atmospherical electricity, was constructed in France by M. de Romas. He procured a kite seven feet long and three feet wide, and elevated it to the height of five hundred and fifty feet. A cloud coming over, the most striking and powerful electrical phenomena presented themselves. Light straws that happened to be on the ground near the string of the kite, began to erect themselves, and to perform a dance between the apparatus and the ground, after the manner of dancing images, as exhibited in ordinary electrical experiments. Art. 691. (5.)

* Cavallo's Complete Treatise on Electricity, II, 22.

At length streams of fire began to dart to the ground, some of which were an inch in diameter, and ten feet long, exhibiting the most terrific appearance.

The foregoing facts evince the abundance of electricity in the atmosphere at particular periods; but experiments of a less formidable kind have been instituted, to ascertain the electrical changes of the air. For this purpose, Mr. Canton, an English philosopher, constructed an ingenious apparatus which warned him of the presence of any unusual quantity of electricity, by causing it to ring a bell connected with the lower extremity of the apparatus.

766. Obvious as is the connection between the phenomena of common electrical apparatus, and those exhibited in the heavens during a thunder storm, yet the identity of lightning with the electric spark, was not dreamed of by the earlier electricians. To Dr. Franklin, is universally conceded the merit of having established this fact, first by reasoning on just principles of analogy, and afterwards by actually bringing down the lightning from the skies. The resemblance between the appearances of lightning and electricity, were thus enumerated.

(1.) The zigzag form of lightning corresponds exactly in appearance with a powerful electric spark, that passes through a considerable interval of air.

(2.) Lightning most frequently strikes such bodies as are high and prominent, as the summits of hills, the masts of ships, high trees, towers, spires, &c. So the electric fluid, when striking from one body to another, always passes through the most prominent parts.

(3.) Lightning is observed to strike most frequently into those substances that are good conductors of electricity, such as metals, water, and moist substances; and to avoid those that are non-conductors.

(4.) Lightning inflames combustible bodies; the same is effected by electricity.

(5.) Metals are melted by a powerful charge of electricity: this phenomenon is one of the most common effects of a stroke of lightning.

(6.) The same may be observed of the fracture of brittle bodies.

(7.) Lightning has been known to strike people blind: Dr. Franklin found, that the same effect is produced on animals, by a strong electric charge.

(8.) Lightning destroys animal life: Dr. Franklin killed turkies of about ten pounds weight, by a powerful electric shock.

(9.) The magnetic needle is affected in the same way by lightning and by electricity, and iron may be rendered magnetic by both causes. The phenomena therefore are strictly analogous, and differ only in degree; but if an electrified gun barrel will give a spark, and produce a loud report at two inches distance, what effect may not be expected from 10,000 acres of electrified cloud? But (said Franklin,) to ascertain the accuracy of these ideas, let us have recourse to experiment. Pointed bodies receive and transmit electricity with facility; let therefore a pointed metal rod be elevated into the atmosphere, and insulated; if lightning is caused by the electricity of the clouds, such an insulated rod will be electrified whenever a cloud passes over it; this electricity may be then compared with that obtained in our experiments.*

767. Such were the suggestions of this admirable philosopher; they soon excited the attention of the electricians of Europe, and having attracted the notice of the King of France, the approbation he expressed excited in several members of the French Academy, a desire to perform the experiment proposed by Franklin, and several insulated metallic rods were erected for that purpose. On the 10th of May, 1752, one of these, a bar of iron forty feet high, situated in a garden at Marly, became electrified during the passage of a stormy cloud over it; and during a quarter of an hour, it afforded sparks, by which jars were charged, and other electrical experiments performed. During the passage of the cloud, a loud clap of thunder was heard, so that the identity of these phenomena was thus completely proved. Similar experiments were made by several electricians in England.

768. Doctor Franklin had not heard of these experiments, and was waiting the erection of a spire at Philadelphia to admit an opportunity of sufficient elevation for his insulated rod, when it occurred to him that a kite would obtain more ready access to the regions of thunder than any elevated building. He accordingly adjusted a silk handkerchief to two light strips of cedar, placed cross-

* Singer.

wise; and having thus formed a kite, with a tail and loop, at the approach of the first storm, he repaired to a field accompanied by his son. Having launched his kite with a pointed wire fixed to it, he waited its elevation to a proper height, and then fastened a key to the end of the hempen cord, and attached this by means of a silk lace (which served to insulate the whole apparatus) to a post. The first signs of electricity which he perceived, was the separation of the loose fibres of the hempen cord: a dense cloud passed over the apparatus, and some rain falling, the string of the kite became wet; the electricity was then collected by it more copiously, and a knuckle being presented to the key, a stream of acute and brilliant sparks was obtained. With these sparks, spirits were fired, jars charged, and the usual electrical experiments performed. Thus was the identity of lightning and electricity, which had been indicated by so many analogies, now established by the most decisive experiments.

769. It is a matter of much importance to the science of Meteorology, (Art. 565.) to ascertain from what *source* atmospherical electricity originates. Among the known sources of this agent none seems so probable, as the evaporation and condensation of watery vapor. We have the authority of two of the most able and accurate philosophers, Lavoisier and La Place, for stating that *bodies in passing from the solid or liquid state to that of vapor, and, conversely, in returning from the aëriform condition to the liquid or solid state, give unequivocal signs of either positive or negative electricity.**

* Dr. Thomson, in his Outlines of Electricity, makes the following note.—M. Pouillet has lately published a set of experiments, which seems to overturn Volta's theory of the evolution of electricity by evaporation. He has shown that no electricity is evolved by evaporation, unless some chemical combination takes place at the same time. But it follows from his experiments, that electricity is evolved abundantly during *combustion*, the burning body giving out resinous, and the oxygen vitreous electricity. In like manner the carbonic acid emitted by vegetables is charged with resinous electricity, and the oxygen (probably) charged with vitreous electricity.—*Thomson's Outlines, p.* 440. But we shall be slow to reject the results of experiments performed by such experimenters as Lavoisier and La Place, especially when confirmed by the testimony of Volta and Saussure.

Combustion is also attended with the evolution of electricity, and even the *friction* of opposite currents of wind, or of a high wind against opposing objects, probably generates more or less of the same agent. The production of electricity during evaporation and condensation may be rendered evident by Coulomb's electrical balance; as may that evolved during the friction of air. If the stem of a tobacco pipe be heated red hot, and a drop of water be introduced by way of the bowl, the jet of steam falling on the brass ball (Fig. 123, *a.*) of the balance will electrify it so that it will set the index of the balance in motion.

It is obvious that a cause which produces only very feeble signs of electricity in so small a quantity of vapor as that which arises from a single drop of water, may still be sufficient to occasion a vast accumulation of the same agent, in such a quantity of vapor as that which is daily ascending into the atmosphere. For it has been calculated, that more than two thousand millions of hogsheads of water are evaporated from the Mediterranean alone in one summer's day.*

Thunder Storms.

770. The following are the *leading facts* respecting the electricity of the atmosphere in relation to this subject, and these are facts which have been established by numerous observers, of the most accurate and diligent class. Beccaria, an Italian electrician, continued his observations on the electricity of the atmosphere for fifteen years with the greatest assiduity; and Cavallo, Read, Saussure, and others, prosecuted the same inquiries with similar zeal.

(1.) Thunder clouds are, of all atmospheric bodies, the most highly charged with electricity. But all single, detached, or insulated clouds, are electrified in greater or less degrees, sometimes positively and sometimes negatively. When, however, the sky is completely overcast with a uniform stratum of clouds, the electricity is much feebler, than in the single detached masses before mentioned. And, since fogs are only clouds near the surface of the earth, they are subject to the same conditions;—a driving fog of limited extent, is often highly electrified.†

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* Singer. † Ed. Encyc. VIII, 310.

(2.) The electricity of the atmosphere is strongest when hot weather succeeds a series of rainy days, or when wet weather succeeds a series of dry days; and during any single day, the air is most electrical when the dew falls before sunset, or when it begins to exhale before sunrise.

(3.) In clear steady weather, the electricity generally remains positive; but in falling or stormy weather, it is constantly changing from positive to negative, or from negative to positive.*

Such are the circumstances of atmospheric electricity in general; next, let us attend to the peculiar phenomena of thunder storms, chiefly as they are exhibited in our own climate.

(1.) In thunder storms there is usually a singular and powerful combination of all the elements,—of darkness, rain, thunder and lightning, and sometimes hail.

(2.) They occur chiefly in the hottest season of the year, and after mid-day; and are more frequent and violent in warm than in cold countries.

(3.) In this State (Connecticut,) thunder storms usually come from the west, either directly, or from the northwest or southwest; but occasionally from the east.

(4.) Violent thunder and lightning are frequently seen in volcanoes and water spouts.

(5.) Thunder storms sometimes descend almost to the surface of the sea, and fall upon the sides of mountains; in which case, they are extremely violent.

(6.) We occasionally observe the following circumstances succeed each other in regular order: first, a vivid flash of lightning,—then a loud peal of thunder,—and, after a short interval, a sudden fall of rain, which sometimes stops as suddenly as it began.†

771. There are in thunder storms evidently two distinct classes of phenomena to be accounted for. The first class consists of the common elements of a storm,—clouds, wind, and rain; the second, of thunder and lightning. The following proposition embraces, in our view, the true explanation of both these classes of phenomena:—

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* Singer, p. 273.

† Morgan's *Lectures on Electricity* contain an excellent view of the natural agencies of electricity.

*The storm itself, including every thing except the electrical appearances, is produced in the same manner as other storms of wind and rain; and the electricity, and of course the thunder and lightning, is owing to the rapid condensation of watery vapor.**

We do not, therefore, consider electricity as the *cause*, but as the *consequence* of the storm; or as a concomitant of the clouds, wind, and rain.

To explain the subject a little more fully, we conceive of the entire process as follows. A sudden rarefaction produced by the intensity of the solar heat, or otherwise, puts the air in motion, that is, raises a wind, blowing in all directions towards the place of greatest rarefaction. Such a meeting of opposite currents, some of which are largely charged with watery vapor, produces a sudden deposition and accumulation of clouds. (Art. 569.) These, when sufficiently driven together and condensed, have their minute floating particles united in drops of rain. When the opposite winds are violent, and the accumulation of clouds great, they become black, as a natural consequence of the thickness of their strata, and the compactness of their mass, and fall towards the earth by their increased weight, until they subside into air sufficiently dense to support them,—sometimes, indeed, falling upon the surface of elevated grounds, and more rarely descending to the general level of the earth. Finally, the rapid changes of state which vapor undergoes in condensation,—a process which is more rapid in proportion as the storm is more violent, and the heat more intense, generate the electricity.

772. Do we then find in thunder storms, the common cause of rain operating, namely, the sudden cooling of warm air, charged with watery vapor?

First, storms of rain have been satisfactorily accounted for, from the meeting of opposite winds of different temperatures. (See

* Other causes, such as friction, change of temperature, &c., may have some influence, but the condensation of vapor, producing electricity, which is accumulated in *insulated* clouds, (thunder clouds being insulated by the circumambient air,) is to be regarded as the chief source of the electricity of thunder storms.

Art. 570.) The more violent of these, especially in tropical countries, are in fact thunder storms; and in places, as Egypt and the western coast of Peru, where, on account of the constancy of the winds it never rains, it likewise never thunders.

Secondly, in the Metorological Register, kept at Yale College, from 1804 to 1822, inclusive, we find recorded one hundred and sixteen thunder storms. Of these ninety nine were immediately preceded or followed by a change of wind, of which fifty were from south to north,—not directly, but in most instances from south-west to north-west. The process on a hot summer's day, is usually as follows. During the earlier part of the day a south-westerly breeze is blowing, which, coming from a warmer region, exposed to the rapid evaporation of a summer's sun, is copiously charged with watery vapor. As the heat advances, the dense and colder air of the north-west is put in motion towards this parallel of greater rarefication. The two opposite winds meet, the warmer current deposits a portion of its watery vapor; at first a calm ensues, when the opposite forces are in equilibrium, afterwards, the northerly portion predominates, dissipates the storm, restores serenity to the sky, and coolness to the air.

Thirdly, we shall hardly meet with any minute and precise description of a thunder storm, without recognising this common circumstance, *the frequent shiftings of the wind*, indicative of the meeting of opposite currents. It is frequently alleged that thunder clouds move against the wind. This we know is impossible; but the expression implies that the two winds, the one at the cloud and the other at the spectator, blow in opposite directions.* The meeting of adverse winds is adequate to explain all the phenomena of thunder storms, viz. the sudden formation and accumulation of clouds, their subsidence to the lower regions of the atmosphere, in consequence of their conglomeration, and the production of torrents of rain, and finally the sudden evolution of vast quantities of the electric fluid, which exhibits itself in lightning and thunder. The clouds themselves being good conductors, while the air with which they are surrounded is a bad conductor, they are of course immense insulated conductors, of which some are charged with positive and some

* Haüy, Natural Phil. I. 425. Encyc. Perthensis, art. *Thunder*.

with negative electricity. (Art. 770.) On their approach to each other, the opposite electricities, conformably to the law of induction, (Art. 713.) rush to the contiguous ends, where they accumulate until they at length discharge themselves through the intervening space of air, often to a great distance, and with a flash proportionally long and vivid, and a report proportionally loud. Most of the explosions are the harmless discharges of electricity from one cloud to another differently electrified.*

773. But the earth itself in its natural state, is a vast conductor, where any excess of the electric fluid may readily discharge itself. Accordingly, where a cloud highly charged comes near to the earth, it puts the latter in the opposite electrical state by induction, and a discharge takes place between the earth and the cloud. When the electricity which is expelled from the earth by the approach of a cloud, returns to it, it sometimes produces a violent shock, and is known by the name of the *returning stroke*. Indeed, in some instances, lightning is supposed to take a circuitous route in its way from one cloud to another, first darting to the earth and thence to the opposite cloud, the distance of the clouds from each other being too great to permit the discharge through the intervening space of air. And since electricity passes quietly without light or noise, when it makes its way through good conductors, and manifests its splendors and mechanical energies only when its path is obstructed by imperfect conductors, it is reasonably inferred that the lightning and thunder have an origin extrinsic to the fluid itself; that the lightning is produced by the sudden and powerful *condensation* which the air experiences when compressed before the fluid, (a known cause of heat and light,) and that the thunder is produced by the *collapsing* of the air, filling the sudden void, occasioned by the passage of the fluid (a known cause of sound).† The zigzag appearance of lightning is well explained by supposing the air so much condensed before it, as to turn its course in another direction, where the same resistance is again experienced and another change encountered. This explanation is rendered the more probable by experiments, which show that the zigzag appear-

* Morgan's Lectures on Elec. 2. 211.

† Cavallo, *Complete Treatise*, p. 274.

ance is very much increased when the electric spark is passed through condensed air, but disappears entirely when it is passed through a vacuum. (Art. 734.)

774. If we now apply these principles to the facts before enumerated, (Art. 770.) we shall find them capable of a clear and satisfactory explanation.

All insulated clouds are electrical in a greater or less degree, because their very formation implies a condensation of watery vapor, and the state of insulation prevents the escape of the electric fluid, that is thus evolved. The electricity is stronger in such insulated detached clouds, some of which are positive, and some negative, than in a sky uniformly overcast, because in the latter case the opposite electricities are neutralized, while in the former they are kept separate. The electricity of the atmosphere is strongest when hot weather suceeds a series of rainy days, and when wet weather succeeds a series of dry days, because then, in both cases, the evaporation is most sudden and abundant; and on a single day, the signs of electricity are strongest at the rising and falling of the dew, that being the very moment when the evaporation in the morning, and the condensation in the evening, are most copious. Thunder showers are most frequent and violent in hot climates, and during the hottest seasons of the year, for in such places and at such times, the causes supposed are in most active operation. Electricity, if evolved at all by slower processes of evaporation and condensation, finds its equilibrium before it can accumulate in sufficient quantity to produce the phenomena of a thunder storm. Thunder storms usually occur after mid-day, because it is chiefly during the hottest part of the day, or a little after it, that the meeting of those opposite currents occurs, which generate the storm; since it is at the places of greatest rarefaction, that this concourse of winds takes place; and therefore during the heat of summer, the sun is sometimes followed round the globe by thunder storms.

775. It has been observed, Art. 770, (3.) that in this State, thunder storms come from some point of the west, and rarely from any other quarter. This is more especially the case with those storms which occur in the afternoon and evening, and when a warm south-

westerly wind precedes the storm, and a cool north-westerly wind follows it. In the heat of summer, the south-westerly is the hottest of all our winds, and the north-westerly is the coldest. The mixture of these, therefore, more than of any other opposite winds, would generate thunder storms. The manner in which the northerly wind is set in motion after mid-day, during the hottest part of summer, has been already adverted to. (Art. 771.) By reflecting for a moment on the conditions of every other kind of wind at that season, it will be seen that there is no one with which, according to our principles, a north-west wind would be so likely to produce a thunder storm, as with one from the south-west, which comes to us after having passed over the heated lands of the south. Suppose that an easterly wind has been prevailing during the earlier parts of the day, and that a north-westerly wind, set in motion towards the places most strongly rarefied by the sun's heat, meets this wind from the east, which, coming from the sea, is at that season comparatively cool. The meeting would be that of *two currents of cool air*, a circumstance far less favorable to the production of a thunder storm than the concourse of a hot current with a cold. If we suppose the northerly wind to meet with a wind from every other quarter of the heavens in succession, we shall find each less favorable for the generation of a storm than that from the south-west. A sudden influx, however, of cold air from the ocean, mixing with the hotter air over the land, produces those occasional easterly thunder storms before mentioned. Art. 770, (3.) Storms of this kind sometimes occur in the morning.

776. In volcanoes, the most vivid lightnings and the heaviest thunders are produced, because here an immense quantity of heated vapor is thrown out, which on reaching the cold regions of the atmosphere is suddenly condensed into thick clouds; and the same phenomena are often terrific in water spouts, because here the sudden formation of clouds and rain, occasions a vast evolution of electricity. Violent thunder storms sometimes fall upon the sides of mountains or upon the surface of the sea, for here, on account of the proximity of the clouds, the discharges are made towards the earth or sea, which, in ordinary cases, are made from cloud to cloud.

777. All the foregoing facts appear to admit of a clear explanation, in conformity with the supposition, that the storm itself, including all the phenomena except the electrical, is produced like other storms of wind and rain, by the sudden cooling of heated air charged with watery vapor, (Art. 570.) and that the electrical phenomena are produced by the condensation of the vapor itself into clouds and rain. But the last fact mentioned, appears to present greater difficulties. We refer to that quick succession of events, Art. 770, (6.) occurring in the following order; namely, first, a vivid flash of lightning—then a loud peal of thunder—and, after a little interval, a sudden fall of rain, which frequently stops as suddenly as it commenced. At first view, it would seem that the rain which follows the electrical discharge is produced by it; whereas, according to the foregoing views, the lightning is not the cause, but rather a consequence of the formation of the rain. (Art. 771.) But suppose that the events were to take place as required by our principles; that drops of rain were suddenly to coalesce, forming a shower, and that the attendant lightning and thunder were produced by this process; let us see in what order the notice of these events would reach the earth. The passage of light being nearly instantaneous, the flash would be seen the instant of the explosion; but sound is a comparatively slow traveller, and would take its own time to reach the ear; and rain, a much slower traveller still, would arrive much later than the other two. To submit these successive events to something like mathematical calculation, we will suppose the cloud to be one fourth of a mile high, and that the precipitation of the rain, and the evolution of the electricity, which causes the explosion, are cotemporaneous events. First, the *flash* would reach us without any perceptible interval. Secondly, the *sound*, travelling at the rate of 1142 feet per second, would require 1.15 seconds to reach the ear. Thirdly, the *rain*, descending like any other falling body, we may calculate its time accordingly. The times being as the square roots of the spaces. $\sqrt{16.1} : 1 :: \sqrt{1320} : 9$ *seconds*. The time would be considerably more than this, on account of the resistance of the air. Our principles, therefore, require that the flash, the report, and the shower, should succeed each other in the order in which they actually occur.

Lightning Rods.

778. Dr. Franklin had no sooner satisfied himself of the identity of electricity and lightning, than, with his usual sagacity, he conceived the idea of applying the knowledge acquired of the properties of the electric fluid, so as to provide against the dangers of thunder storms. The conducting power of metals, and the influence of pointed bodies, to collect and transmit the fluid, naturally suggested the structure of the Lightning Rod. The experiment was tried and has proved completely successful; and probably no single application of scientific knowledge ever secured more celebrity to its author.

779. Lightning rods are at present usually constructed of wrought iron about three fourths of an inch in diameter. The parts may be made separate, but, when the rod is in its place, they should be screwed together so as to fit closely, and to make a continuous surface, since the fluid experiences much resistance in passing through links and other interrupted joints. At the bottom, the rod should terminate in two or three branches, going off in a direction from the building. The depth to which it enters the earth should not be less than five feet; but the necessary depth will depend somewhat on the nature of the soil: wet soils require a less, and dry soils a greater depth. In dry sand it must not be less than ten feet; and in such situations, it would be better still to connect, by a convenient conducting communication, the lower end of the rod with a well or spring of water. It is useful to fill up the space around the part of the rod that enters the ground, with coarsely powdered charcoal, which at once furnishes a good conductor, and preserves the metal from corrosion. The rod should ascend above the ridge of the building to a height determined by the following principle: that *it will protect a space in every direction from it, whose radius is equal to twice its height*. It is best, when practicable, to attach it to the chimney; which needs peculiar protection, both on account of its prominence, and because the products of combustion, smoke, watery vapor, &c. are conductors of electricity. For a similar reason a kitchen chimney, being that in which the fire is kept during the season of thunder storms, requires to be especially protected. The rod is terminated above in three forks, each of which ends in a sharp point. As these

points are liable to have their conducting power impaired by rust, they are protected from corrosion by being covered with gold leaf; or they may be made of solid silver or platina. Black paint being made of charcoal, it forms a better coating for the rod than paints made of other colors, the bases of which are worse conductors. The rod may be attached to the building by *wooden* stays. Iron stays are sometimes employed, and in most cases they would be safe, since electricity pursues the most direct route (Art. 745.); but in case of an extraordinary charge, there is danger that it will divide itself, a part passing into the building through the bolt, especially if this terminates in a point. Buildings furnished with lightning rods have occasionally been struck with lightning; but on examination it has generally, if not always, been found that the structure of the rod was defective; or that too much space was allotted for it to protect. When the foregoing rules are observed, the most entire confidence may be reposed in this method of securing safety in thunder storms.

CHAPTER VIII.

PRECAUTIONS FOR SAFETY DURING THUNDER STORMS—ANIMAL ELECTRICITY—CONCLUDING REMARKS.

780. The great number of pointed objects that rise above the general level, in a large city, have the effect to dissipate the electricity of a thunder cloud, and to prevent its charge from being concentrated on any single object. Hence damage done by lightning is less frequent in a populous town, than in solitary buildings. For similar reasons, a great number of ships, lying at the docks, disarm the lightning of its power, and thus avert the injury to which the form of their masts would otherwise expose them. A solitary ship on the ocean, unprotected by conductors, would appear to be peculiarly in danger from lightning; but, while the greater number of ships that traverse the ocean are wholly unprotected, accidents of this kind are comparatively rare. The reason probably is, that water being a better conductor than wood, the course of the discharge towards

the water is not easily diverted, and will not take the mast in its way unless the latter lies almost directly in its course.—Barns are peculiarly liable to be struck with lightning, and to be set on fire; and as this occurs at a season when they are usually filled with hay and grain, the damage is more serious, for the quantity of combustible matter they contain, is such as to render the fire unmanageable. Professor Silliman ascribes this liability of barns to be struck with lightning, to the influence of the evaporation that proceeds from the fresh hay, &c. which is supposed to furnish a conducting medium like the smoke of a chimney.*

781. Silk dresses are sometimes worn with the view of protection by means of the insulation they afford. They cannot, however, be deemed very effectual unless they completely envelop the person; for if the head and the extremities of the limbs be exposed, they will furnish so many avenues to the fluid as to render the insulation of the other parts of the system of little avail. The same remark applies to the supposed security that is obtained by sleeping on a feather bed. Were the person situated *within* the bed, so as to be entirely enveloped by the feathers, they would afford some protection; but if the person be extended on the surface of the bed, in the usual posture, with the head and feet nearly in contact with the bedsted, he would rather lose than gain by the non-conducting properties of the bed; since, being a better conductor than the bed, the charge would pass through him in preference to that.† The horizontal posture, however, is safer than the erect; and if any advantage on the whole is gained by lying in bed during a thunder storm, it probably arises from this source. The same principle suggests a reason why men or animals are so frequently struck with lightning when they take shelter under a tree during a thunder storm. The fluid first strikes the tree, in consequence of its being an elevated and point-

* American Journal of Science, Vol. III. p. 345.

† Security to the person might be obtained by an entire covering of either a very bad or a very good conductor. In the former case, the electricity would not approach the system; in the latter case it would confine itself to the covering. Clothes when very wet have been supposed to furnish a protection on this principle. (See an interesting case stated by Professor Hitchcock, Amer. Jour. Science.)

ed object, but it deserts the tree on reaching the level of the man or animal, because the latter is a better conductor than the tree.

Tall trees situated near a dwelling house, furnish a partial protection to the building, being both better conductors than the materials of the house, and having the advantage of superior elevation.

782. The protection of chimneys is of particular importance, for to these a discharge is frequently determined. When a fire is burning in the chimney, the vapor, smoke, and hot air, which ascend from it (as has been intimated in article 779,) furnish a conducting medium for the fluid; but even when no fire is burning, the soot that lines the interior of a chimney, is a good conductor, and facilitates the passage of the discharge.

It is quite essential, during a thunder storm, to avoid every considerable mass of water, and even the streamlets that have resulted from a recent shower; for these are all excellent conductors, and the height of a human being, when connected with them, is very likely to determine the course of an electric discharge. The partial conductors, through which the lightning directs its course, when it enters a building, are usually the appendages of the walls aud partitions; the most secure situation is therefore the middle of the room, and this situation may be rendered still more secure by standing on a glass legged stool, a hair mattress, or even a thick woollen rug. The part of every building least liable to receive injury, is the middle story, as the lightning does not always pass from the clouds to the earth, but is occasionally discharged from the earth to the clouds. Hence it is absurd to take refuge in a cellar, or in the lowest story of a house; and many instances are on record in which the basement story has been the only part of the building that has sustained severe injury. Whatever situation be chosen, any approach to the fire place should be particularly avoided.* An open door or window is an unsafe situation, because the lightning is apt to traverse the large timbers that compose the frame of the house, and would be determined towards the animal system on account of its being a better conductor. In a carriage the passenger is safer in the central part than next to the walls; but a carriage may be effectually protected by attaching to its

* Singer.

upper surface metallic strips connected with the wheel tire. The fillets of silver plating which are frequently bound round the carriage, may be brought into the conducting circuit.

Animal Electricity.

783. Of the natural agencies of electricity, one of the most remarkable, is that exhibited by certain species of fish, especially the *Torpedo* and the *Gymnotus*. This peculiar property of the Torpedo was known to the ancient naturalists, and is accurately described by Aristotle and by Pliny. Aristotle says that this fish causes or produces a torpor upon those fishes it is about to seize, and having by that means got them into its mouth, it feeds upon them. Pliny says that this fish, if touched by a rod or spear, even at a distance, paralyzes the strongest muscles.

784. The fact, however, that this extraordinary power depended upon electricity, was not known until about the year 1773, when it was ascertained by Mr. Walsh, that the Torpedo was capable of giving shocks to the animal system, analogous to those of the Leyden Jar. Though this property is regarded as establishing the identity of the power with the electric fluid, yet this power, as developed in the Torpedo, has never been made to afford a spark, nor to produce the least effect upon the most delicate electrometer.* As late as the year 1828, experiments were made upon the Torpedo, by Sir Humphry Davy, and the conclusions to which he arrived, were that the electricity resides in this animal in a form suited exclusively to the purpose of communicating shocks to the animal system, while it has little or nothing else in common with the properties of electricity, as developed in various artificial arrangements.†

The Torpedo is a flat fish, seldom twenty inches in length, but one found on the British coast was four and a half feet long. The electricity of the Torpedo has the same relation as common electricity to bodies in respect to their conducting power, being readily transmitted

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* Humboldt.

† Phil. Trans. 1829. A reflection naturally suggested by this fact is, that the fluid which is excited in the various species of electrical apparatus, both the common and Voltaic, is a compound, embracing several distinct substances.

through metals, water, and other conductors, and not being transmitted through glass, and other non-conductors.

785. The *electric organs* of the Torpedo are two in number, and placed one on each side of the cranium and gills. The length of each organ is somewhat less than one third part of the length of the whole animal. Each organ consits of perpendicular columns reaching from the under to the upper surface of the body, and varying in length according to the various thickness of the flesh in different parts. The number of these columns is not constant, being not only different in different Torpedos, but likewise in different ages of the animal, new ones seeming to be produced as the animal grows. In a very large Torpedo, one electric organ has been found to consist of one thousand one hundred and eighty two columns. The diameter of a column is about one fifth of an inch. Each column is divided by horizontal partitions, consisting of transparent membrane, placed over each other at very small distances, and forming numerous interstices, which appear to contain a fluid. The number of partitions contained in a column one inch in length, has been found in some instances not less than one hundred and fifty. By this arrangement, the amount of electrified *surface*, is exceedingly great; equivalent in one instance, to one thousand and sixty four feet of coated glass. Hence, the effects of the electricity of the Torpedo are such as correspond to those which, in artificial arrangements, are produced by diffusing a given quantity of fluid over a great surface, by which its intensity is much diminished.

786. The *Gymnotus*, or Surinam eel, is found in the rivers of South America. Its ordinary length is from three to four feet; but they are said to be sometimes twenty feet long, and to give a shock that is instantly fatal. The electrical organs of the Gymnotus, constitute more than one third part of the whole animal; they consist of two pairs, of different sizes and placed on different sides. The shock communicated to fishes instantly paralyzes them, so that they become the prey of the Gymnotus. By irritating the animal with one hand while the other is held at some distance in the water, a shock is received, as severe as that of the Leyden Jar.

Unlike the Torpedo, the Gymnotus gives a small but perceptible spark, affording additional proof of the identity of the power with that of electricity.

M. Humboldt, in his travels in South America, describes a singular method of catching the Gymnotus, by driving wild horses into a lake which abounds with them. The fish are wearied or exhausted by their efforts against the horses, and then taken; but such is the violence of the charge which they give, that some of the horses are drowned before they can recover from the paralyzing shocks of the eels.

The *Silurus Electricus*, is a fish found in some of the rivers of Africa. Its electrical powers are inferior to those of the Torpedo and Gymnotus, but they are still sufficient to give a distinct shock to the human system.

787. Certain furred animals, particularly the cat, become spontaneously electrified. This is more especially observable on cold windy nights, when the state of the air is favorable to insulation. At such times a cat's back will frequently afford electrical sparks. Ancient historians mention a number of very remarkable occurrences, of good or evil omen, which are due to the electricity of the atmosphere. Herodotus informs us that the Thracians disarmed the sky of its thunder, by throwing their arms into the air; and that the Hyperboreans produced the same effect, by launching among the clouds darts armed with points of iron. Cæsar in his Commentaries, says that in the African war, after a tremendous storm which threw the whole of the Roman army into great disorder, the points of the darts of a great number of the soldiers shone with a spontaneous light. In the month of February (says he) about the second watch of the night, there suddenly arose a great cloud, followed by a dreadful storm of hail, and in the same night the points of the darts of the fifth legion appeared on fire.*

During a dry snow storm, when electricity is evolved in great quantities, and, on account of the dry state of the air, is partially insulated on conducting bodies, similar appearances are exhibited. Thus the ears of horses and various pointed bodies emit faint streams of light. These phenomena are sometimes exhibited in a most striking manner in a storm at sea, when the masts of a ship, yard arms, and every other pointed object are tipped with lightning.†

* Ed. Encyc. VIII. 311. † See Jones' Naval Sketches, I. 199.

Concluding Remarks.

788. From the energy which electricity displays in our experiments, and much more in thunder storms, there can be no question that it holds an important rank among the ultimate causes of natural phenomena. Its actual agencies, however, are liable to be misinterpreted, and that they have been so in fact, is too manifest from the history of the science. After the splendid experiments with the Leyden Jar, and more especially, after the identity of electricity with lightning had been proved, electricians fancied that they had discovered the clue which would conduct them safely through the labyrinth of nature. Every thing not before satisfactorily accounted for, was now ascribed to electricity. They saw in it not only the cause of thunder storms, but of storms in general; of rain, snow, and hail; of whirlwinds and water spouts; of meteors and the aurora borealis; and, finally, of tides and comets, and the motions of the heavenly bodies. Later electricians have found in the same agent the main spring of animal and vegetable life, and the grand catholicon which cures all diseases. Recent attempts have been made to establish the very identity of galvanic electricity and the nervous influence, by which the most important functions of animal life are controlled.*

Among the most important of the agencies of electricity in the economy of nature, is that which, according to the views of Sir Humphry Davy, it sustains in relation to the chemical agencies of bodies. Chemical and electrical attractions, he supposes, are one and the same thing, or at least dependent on the same cause, the attraction between the elements of a compound arising solely from their being naturally in opposite electrical states. But the discussion of this hypothesis belongs more appropriately to Galvanism, a branch of our subject which, on account of its peculiarities, especially in the mode of excitation, has been constituted a separate department of science.†

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* *Wilson Philip*, Phil. Trans. Tilloch's Phil. Mag. XXX, 488.

† In the distribution of subjects in Yale College, Galvanism is assigned to the chemical department. If, however, it should appear necessary, for the convenience of other Institutions who may use this Treatise, to have that subject included in it, the outlines of Galvanic electricity may be added in the appendix.

PART V.—MAGNETISM.

789. MAGNETISM *is the science which treats of the properties and effects of the magnet.*—The same term is also used to denote the unknown cause of magnetic phenomena; as when we speak of magnetism as excited, imparted, and so on.

Magnets are bodies, either natural or artificial, which have the property of attracting iron, and the power, when freely suspended, of taking a direction towards the poles of the earth.

The natural magnet is sometimes called the *loadstone.** It is an oxide of iron of a peculiar character, found occasionally in beds of iron ore. Though commonly met with in irregular masses only a few inches in diameter, yet it is some times found of a much larger size. One recently brought from Moscow to London, weighed one hundred and twenty five pounds, and supported more than two hundred pounds of iron.†

790. The *attractive* powers of the loadstone have been known from a high antiquity, and are mentioned by Homer, Pythagoras, and Aristotle. But the *directive* powers were not known in Europe, until the thirteenth century, when they were discovered by a Neapolitan named Flavio; though some writers have endeavored to trace the history of the compass needle to a remoter period, and some have strenuously maintained that the Chinese were in possession of it many centuries before it was known to Europeans.‡

Magnetism is the most recent of all the physical sciences, and notwithstanding the numerous discoveries achieved in it within a few years, and the remarkable precision with which its laws have been ascertained, yet it is still to be regarded as a science quite in its infancy, although it is rapidly progressive.

* Said to be derived from *lædan*, a Saxon word which signifies *to guide.* † Partington's Manual, II. 243.

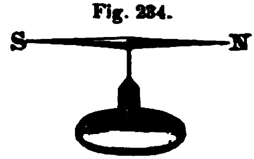
‡ Cavallo, *on Magnetism;* Barlow, *Encyc. Metrop.*

791. If a magnet be rolled in iron filings, it will attract them to itself. This effect takes place especially at two opposite points, where a much greater quantity of the filings will be collected than in any other parts of the body. The two opposite points in a magnet, where its attractive powers appear chiefly to reside, are called its *poles*. The straight line which joins the poles, is called the *axis*. (See Fig. 233.)

Fig. 233.

If a large sewing needle or a small bar of steel be rubbed on the loadstone, one extremity on one pole, and the other extremity on the other, the needle or bar will itself become a magnet, capable of exhibiting all the properties of the loadstone. Without staying at present to describe more minutely the process of making artificial magnets, we will suppose ourselves provided with several magnetic needles and bars, and we may proceed with them to study the leading facts of the science of magnetism. By attaching a fine thread to the middle of a needle, and suspending it so as to move freely in a horizontal plane; or by resting it on a point, as is represented in figure 234, we shall have a simple and convenient apparatus for numerous experiments. The needle thus suspended will place itself in a direction nearly, though not exactly, north and south. If the needle is drawn out of the position it assumes when at rest it will vibrate on either side of that position until it finally settles in the same line as before, one pole always returning towards the north, and the other towards the south. Hence the two poles are denominated respectively *north and south poles*. In magnets prepared for experiments, these poles are marked either by the letters N and S, or by a line drawn across the magnet near one end, which denotes that the adjacent pole is the north pole.

Fig. 234.



792. By means of the foregoing apparatus we may ascertain that the magnet has the following general properties, viz.

First, powers of attraction and repulsion.

Secondly, the power of communicating magnetism to iron or steel by induction.

Thirdly, polarity, or the power of taking a direction towards the poles of the earth.

Fourthly, the power of inclining itself towards a point below the horizon, usually denominated the *dip of the needle.*

The farther developement of these properties will constitute the subjects of the following chapters.

CHAPTER I.

OF MAGNETIC ATTRACTION.

793. *When either pole of a magnet is brought near to a piece of iron, a mutual attraction takes place between them.*

Thus, when the ends of a magnetic bar or needle are dipped into a mass of iron filings, these adhere in a cluster to either pole. A bar of soft iron, or a piece of iron wire, resting on a cork, and floating on the surface of water or quick-silver, may be led in any direction by bringing near to it one of the poles of a magnet. This action is moreover *reciprocal*, that is, the iron attracts the magnet with the same force that the magnet attracts the iron. If the two bodies be placed on separate corks and floated, they will approach each other with equal momenta; or if the iron be held fast, the magnet will move towards it.

794. Two other metals beside iron, namely, nickel and cobalt, are susceptible of magnetic attraction. These metals, however, exist in nature only in comparatively small quantities, and therefore by magnetic bodies, are usually intended such as are ferruginous. Even iron, in some of its combinations with other bodies, loses its magnetic properties; only a few of the numerous ores of iron are attracted by the magnet. But soft metallic iron, and some of the ores of the same metal, affect the needle even when existing in exceedingly small quantities, so that the magnet becomes a very delicate test of the presence of iron. Compass needles are sometimes said to be disturbed by the minute particles of steel left in the dial plate by the graver;*

* Eaton, American Journal Science, Vol. XIV. p. 15.

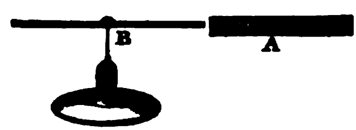
and the proportion of iron in some minerals may be exactly estimated by the power they exert upon the needle.*

795. *In the action of magnets on each other, poles of the same name repel, those of different names attract each other.*

Thus the north pole of one magnet will repel the north pole of the other, and attract its south pole. The south pole of one will repel the south pole of the other and attract its north pole. These effects, it will be perceived, are analogous to those produced by the two species of electricity; and they equally imply two species of magnetism or two magnetic fluids (as it is convenient to call them) namely, the northern, and the southern, or as they are now denominated the *boreal* and the *austral* fluids.

796. *By bringing a magnet near to iron or steel, the latter is rendered magnetic by Induction.*

Fig. 235.



Thus, let the north pole of a magnetic bar A, (fig. 235.) be brought near to one end of an unmagnetized bar of soft iron B: the iron will immediately become itself a magnet, capable of attracting iron filings, having polarity when suspended, and possessing the power of communicating the same properties to other pieces of iron. It is, however, only while the iron remains in the vicinity of the magnet, that it is endued with these properties; for let the magnet be withdrawn and it loses at once all the foregoing powers. This, it will be remarked, is asserted of *soft iron*; for steel and hardened iron are differently affected by induced magnetism.

On examining the kind of magnetism induced upon the two ends of the iron bar B, (fig. 235.) which we may easily do by bringing near to it the poles of the needle, (fig. 234.) we shall find that the nearer end has south, and the remoter end north polarity. This effect also is analogous to that produced by electrical induction.† A correspond-

* Biot.

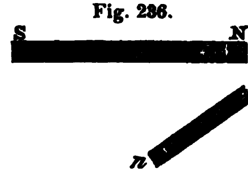
† See Arts. 713—720.

ing effect would have taken place, had the south instead of the north pole of the magnet been presented to the bar of iron; in which case, the nearer end would have exhibited northern, and the remote end southern polarity. Or, to express this important proposition in general terms,

Each pole of a magnet induces the opposite kind of polarity in that end of the iron which is nearest to it, and the same kind in that end which is most remote.

797. It is not essential to the success of these experiments, that the bars of iron which receive magnetism by induction, should be placed in a straight line with the magnet: they may be at right angles to it or inclined at any other angle, the only essential condition being that the end of the bar should be brought near to the pole of the magnet. Indeed the effect is increased, that is, the magnetism of the iron bar is rendered stronger, when the bar is inclined towards the magnet, as in figure 236, and is strongest of all when it is placed parallel to the magnet; for it will be seen that in these two latter positions, both poles of the magnet conspire in their action upon the iron bar.

Fig. 236.



798. *The power of a magnet is increased, by the exertion of its inductive power upon a piece of iron in its neighborhood.*

The end of the piece of iron contiguous to the pole of the magnet, is no sooner endued with the opposite polarity, than it reacts upon the magnet and increases its intensity, and a series of actions and re-actions take place between the two bodies, similar to what occurs in electrical induction.* On this account the powers of a magnet are increased by action, and impaired or even lost by long disuse. By adding, from time to time, small pieces of iron to the weight taken up by a magnet, its powers may be augmented greatly beyond their original amount. Hence, the force of attraction of the dissimilar poles of two magnets, is greater than the force of repulsion

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* See Art. 713, &c.

of the similar poles; because, when the poles are unlike, each contributes to enhance the power of the other, but when they are alike, the influence which they reciprocally exert, tends to make them unlike, and of course to impair their repulsive energies.

Hence, also a strong magnet has the power of reversing the poles of a weak one. Suppose the north pole of the weaker body to be brought into contact with the north pole of the stronger; the latter will expel north polarity, or the boreal fluid, and attract the austral, a change which in certain cases will be permament.

If the north pole of a magnetic bar be placed upon the middle of an iron bar, the two ends of the latter will each have north polarity while the part of the bar immediately in contact with the magnet receives south polarity; and if the same north pole be placed on the center of a circular piece of iron, all parts of the circumference will be endued with north polarity while the plate will have a south pole in the center. By cutting the plate into the form of a star, each extremity of the radii becomes a weak north pole when the north pole of a magnet is placed in the center of the star. If an iron bar is placed between the dissimilar poles of two magnetic bars, both of the magnets will conspire to increase the intensity of each pole of the bar, and the magnetism imparted to the bar will be considerably stronger than from either magnet alone; but if the same bar be placed between the two similar poles, the opposite polarity will be imparted to each end, while the same polarity is given to the center of the bar. Thus if the bar be placed between the north poles of two magnets, each end of the bar will become a south pole and the center a north pole. When one end of a magnetic bar is applied to the ends of two or more wires or sewing needles, the latter arrange themselves in radii diverging from the magnetic pole. This effect is in consequence of their remoter ends, becoming endued with similar polarity, and repelling each other. A like effect is observable among the filaments of iron filings, that form a tuft on the end of a magnetic bar.

799. The foregoing experiments are sufficient to show that when a piece of iron is attracted by the magnet, it is first itself converted into a magnet by the inductive influence of the magnetising body. Each of the iron filings which compose the tuft at the pole of a magnetic bar or needle, is itself a magnet and in consequence of being

such, induces the same property in the next particle of iron, and that in the next, and so on to the last. Hence magnetic attraction does not exist, strictly speaking, between a magnet and iron, but only be-between the opposite poles of magnets; for the iron must first become a magnet before it is capable of magnetic influence.

800. *Soft iron readily acquires magnetism and as readily loses it; hardened steel acquires it more slowly, but retains it permanently.*

In the preceding examples, the magnetism acquired by a bar of iron, by the process of induction, is retained only so long as the magnetising body acts upon it. Soon after the two bodies are separated the bar loses all magnetic properties.

When a bar of steel is placed very near a strong magnet, the action of the magnet commences immediately upon the end of the bar nearest to it, the north pole for example communicating south polarity to the contiguous extremity of the bar. According to our previous experience, we should expect to find the remote end of the bar a north pole; but such is not the *immediate* result; a sensible time is required before the north polarity is fully imparted to the remote extremity. Indeed if the bar be a long one, it sometimes happens that the northern polarity never reaches the farthest end, but stops short of it at some intermediate point. This north pole is succeeded by a second south pole, that by another north pole, and thus several alternations between the two poles occur before reaching the end of the bar.

801. The process of magnetizing a steel bar or needle is accelerated by any cause which excites a tremulous or vibratory motion among the particles of the steel. Striking on the bar with a hammer promotes the process in a remarkable degree, especially if it occasions a ringing sound, which indicates that the particles are thrown into a vibratory motion. The passage of an electric discharge through a steel bar under the influence of a magnet, produces permanent magnetism. Heat also greatly facilitates the introduction of the magnetic fluid into steel. The greatest possible degree of magnetism that can be imparted to a steel bar is communicated by first heating the steel to redness, and while it is under the influence of a strong magnet, quenching it suddenly with cold water.

802. A magnet, however, loses its virtues by the same means as, during the process of induction, were used to promote their acquisition. Accordingly any mechanical concussion, or rough usage impairs or destroys the powers of a magnet. By falling on a hard floor, or by being struck with a hammer it is greatly injured. Heat produces a similar effect. A boiling heat weakens and a red heat totally destroys the power of a needle. On the other hand, cold augments the powers of the magnet; indeed they improve with every reduction of temperature hitherto applied to them.*

As iron and steel are found of various degrees of hardness, so their powers of acquiring and of losing magnetism is very various in different ferruginous bodies. It is in general true, that this power is in proportion to the hardness. Thus, the attraction of soft malleable iron for the magnet being 100, that of hard cast steel is only 49, and that of cast iron only 48.†

803. *If a steel bar, rendered magnetic by induction, be divided into any two parts, each part will be a complete magnet, having two opposite poles.*

We here meet with a remarkable distinction between magnetic and electric induction. When a body electrified by induction, is divided into two equal parts, the individual electricities alone remain in each part respectively; but in the case of magnetic induction, although no appearance of polarity be exhibited except at the two ends, yet wherever a fracture is made, the two ends separated by the fracture immediately exhibit opposite polarities, each being of an opposite name to that of the original pole at the other end of the fragment. If each of the two fragments be again divided into any number of parts, each of these parts is a magnet perfect in itself, having two opposite poles.

In magnetism therefore, there is never as in electricity, any *transfer* of properties, but only the excitation of such as were already inherent in the body acted upon. Magnetism never passes out of one body into another; nor can we ever obtain a piece of iron or steel that contains exclusively either northern or southern polarity.

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* *Christie*, Phil. Trans. 1825. † Barlow.

804. *The force of attraction, or of repulsion, exerted upon each other by the poles of two magnets, placed at different distances, varies inversely as the square of the distance.*

This law was ascertained by Coulomb by means of the torsion balance, in a manner similar to that adopted in investigating the law of electrical attraction; (see Art. 697.) The same law therefore, which governs the attraction of gravitation, likewise controls electrical and magnetic attractions. It is the most extensive law of the physical world. Nor is this action at a distance prevented, or even impaired, by the interposition of other bodies not themselves magnetic.

805. *The magnetic power of iron resides wholly on its* SURFACE, *and is independent of the mass.*

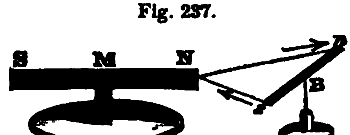
Thus a hollow globe of iron of a given surface, will have the same effect on the needle as though it were solid throughout. In this fact we again meet with a striking analogy between magnetism and electricity, the same property having before been shown to belong to the electric fluid. This is one of the most recent discoveries in magnetism, and was made by Professor Barlow of the Military Academy at Woolwich, (Eng.) to whose ingenious and assiduous labors are due many of the latest and most important investigations in this science.

CHAPTER II.

OF THE DIRECTIVE PROPERTIES OF THE MAGNET.

806. *If a small needle be placed near one of the poles of a magnet with its center in the axis of the magnet, it will take a direction in a line with that axis.*

Fig. 237.



Thus let S N be a large magnetic bar and *s n* a small needle placed near the north pole of the magnet with its center in the axis: it will be seen that the action of the pole of the magnet is such as to bring the needle into a line with the

magnet. The action of the bar upon the needle tending to give it this direction, is equal to the sum of its actions upon both poles; while the attraction of the bar upon the whole needle, being only that by which the attraction for *s* on account of its nearness, exceeds the repulsion of *n*, must be less than the directive force.

807. *If the needle be placed at right angles to the bar with one of its poles directed towards the center of the bar, it will take a direction parallel to the bar.*

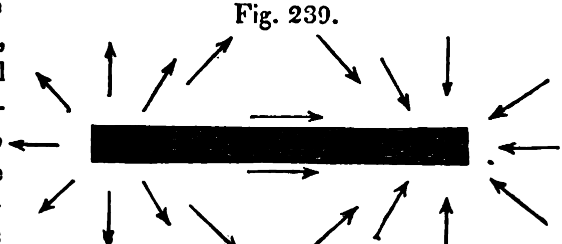
By supposing B (Fig. 237,) to be placed as indicated in the above proposition, it will be seen, that the actions of both poles of the magnet would conspire in relation to each pole of the needle, and that these forces can be in equilibrium only when the needle is parallel with the bar. The needle in this situation has a tendency to move towards the magnet, because the attractions being exerted on the nearer and the repulsions on the remoter poles, the sum of the attractions exceeds that of the repulsions.

808. *Iron filings or other ferruginous bodies, which are free to obey the action of a magnetic bar, naturally arrange themselves, in curve lines from one pole of the magnet to the other.*

Fig. 238.

Thus, if we place a sheet of white paper on a magnetic bar laid on the table and sprinkle iron filings on the paper, the filings will arrange themselves in curves around the poles of the magnet. A small sewing needle suspended horizontally by a slender string, on being brought near to different parts of the magnet will take directions corresponding to the part of the curve in which it happens to be placed. At the poles it will be in a line with the axis of the magnet; opposite the center of the bar, it will be parallel to it; and between these two points, it will take intermediate directions, as is represented in figure 239.

Fig. 239.



These curves have given rise to the most fanciful theories of magnetism, having been assumed as the traces of an invisible fluid perpetually circulating between the poles of the magnet; and this circulation has been afterwards employed for illustrating every variety of magnetic phenomena, but in such a way as to leave the subject involved in greater mystery than at first. These causes are nothing more than the necessary result of forces like those described in the foregoing propositions.*

The curves which iron filings describe when thus arranged are called *magnetic curves*. They present several curious properties which have been investigated by mathematicians; but we must refer the student to more extensive treatises than the present for a full development of this subject.†

809. *The magnetic needle when freely suspended seldom points directly to the pole of the earth, but its deviation from that pole is called the* DECLINATION, *or the* VARIATION *of the needle.*

A vertical circle drawn through the line in which the needle naturally places itself, is called the *magnetic meridian*. A plane passing at right angles to the magnetic meridian, through the center of the needle, is called its *magnetic equator*. A line drawn on the surface of the earth passing through the places where the needle points directly to the north pole, and where of course the geographical and magnetic meridians coincide, is called the *line of no variation*.

The discovery of the variation of the needle, has been commonly ascribed to Columbus. His son Ferdinand states, that on the 14th of September, 1492, his father first discovered the variation, and that in consequence his crew mutinied, supposing that the needle had lost its polarity and that they would not be able to find their way back to Europe. It appears however that the same phenomenon had been discovered about two hundred years before that period, though it had not become generally known to navigators.‡

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* Barlow.

† *Journal of the Royal Institution*, Feb. 1831.—*Leslie's Geometrical Analysis*.

‡ *Cavallo*, Treatise on Magnetism, *supplement*.

810. ***The declination of the needle is not constant, but is subject to a small annual change, which carries it to a certain limit on one side of the pole of the earth, when it becomes stationary for a time, and then returns to the pole and proceeds to a certain limit on the other side of it occupying a period of many years during each vibration.***

At London, in the year 1580, the needle pointed 11¼ degrees to the east of north; in 1657 it pointed directly to the pole; after which period, it continued to move westward for one hundred and fifty seven years, until the year 1814, when its western declination was nearly 24½ degrees; since 1814, it has been moving slowly eastward. If it takes as many years to return as it did to move from the pole to its western limit, it will reach the pole again in the year 1971; and should it proceed as far eastward as it did westward, and occupy as long a time, it will reach its eastern limit in 2128. The total arc of declination will be $48^{\circ}\ 35'\ 48''$, and the period occupied in passing over it, three hundred and fourteen years. This would be an average of $9'\ 17''$ annually. But the annual variation is much smaller than this towards its eastern and western limits, but much greater when the needle is in the vicinity of the line of no variation. Thus during the nine years that elapsed between 1814 and 1823, the progress eastward is only $11'\ 22''$ or only $1'\ 1.6''$ annually, while from 1657 to 1672 a period of fifteen years, the declination west amounted to $2^{\circ}\ 30'$, or $10'$, annually; and between 1692 and 1722, the annual increase of declination was $16'\ 40''$. It performed half the amount of its western declination in fifty seven years, while to complete the other half, occupied one hundred years.*

In the United States, the variation of the needle, is given for different places as follows:—

At Salem, Massachusetts,	1810, $6^{\circ}\ 22'\ 35''$.	—*Bowditch.*
New Haven, Connecticut,	1820, 4 25 25 .	—*Fisher.*
Albany, New York,	1825, 6 0 0 .	—*Dewitt.*

The annual variation is $2'\ 49''$, by which quantity the needle approaches the pole.

* Thomson, *Outlines of Heat, Elec. and Mag.* p. 545.

Mr. Dewitt, Surveyor General of the State of New York, supposes that the needle took a retrograde course at Albany and other places in the same state, about the year 1807, and that since that period, it has been moving westward. But according to the observations of Dr. Bowditch and of the late Prof. Fisher, the progress of the needle is still towards the pole.*

The variation of the needle however is not the same at the same time in all parts of the earth, but every place has its particular declination. For instance, if we sail from the Straits of Gibraltar to the West Indies, in proportion as we recede from Europe and approach America, the compass will point nearer and nearer due north; and when we reach a certain part of the Gulf of Mexico it will point exactly north. But if we sail from Great Britain to the southern coast of Greenland, we shall find the needle deviates farther and farther form the north, as we approach Greenland, where the deviation will not be less than 45° or 50°.† In some parts of Baffin's Bay the needle points nearly due west.

811. The *line of no variation* encompasses the globe, but its course is subject to numerous irregularities. The position of the north magnetic pole, where it may be supposed to commence, is not exactly ascertained, but it lies in the northeastern part of Hudson's Bay.‡ Proceeding southwards it crosses the United States, passing a little to the eastward of Barbadoes, and touching the northeastern extremity of South America. Thence it extends across the Southern Atlantic towards the south pole, where navigators have not been able to trace it. It appears again in the eastern hemisphere to the south of Van Dieman's Land, and passes across the western part of New Holland. It afterwards divides into two branches, one of which strikes the Continent of Asia at Cape Comorin, and extends across Hindostan, Persia, and the western part of Siberia to Lapland and the Northern Ocean. The other branch pursues a course more nearly north, through China, Chinese Tartary and the eastern part of Siberia.§ In that hemisphere which comprehends Europe, Africa, and the western parts of Asia, together with the greater part of the Atlan-

* American Journal of Science, Vol. XVI, p. 60.

† Thomson, *Outlines*, p. 543. ‡ Sabine. § Biot.

tic, the variation is to the west. In the opposite hemisphere, which comprises the whole of the American Continents both north and south, and the entire Pacific Ocean, together with a certain portion of Eastern Asia, the variation is to the east.*

812. *Beside the annual variation the magnetic needle is subject to daily changes called the* DIURNAL VARIATION.

The deviation of the horizontal needle from its mean position is easterly during the forenoon, and arrives at its maximum about eight o'clock. Thence it returns rapidly to its mean position, which it reaches between nine and ten o'clock, and then its variation becomes westerly; at first increasing rapidly, so as to reach its maximum at about one o'clock in the afternoon, and then slowly receding during the rest of the day, and arriving at its mean position about ten o'clock at night. These changes of declination during the day are connected with changes of temperature, aud their amount is greater in the warmer season of the year, and greatest of all in the month of July or August. Its amount rarely exceeds 12′, and is usually much less than that.† A very accurate series of observations on the Diurnal Variation, was kept by Col. Beaufoy of England and continued for two and a half years, 1817, 18 and 19, with the following general results.

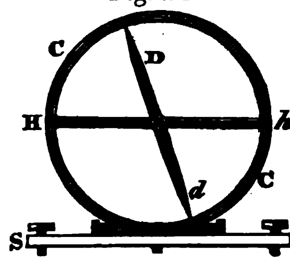
Time of Obs..	*Declination.*	*Difference.*
Morning, - -	24° 14′ 39″ - -	———
Noon, - - -	24 21 54 - - -	7′ 15″
Evening, - -	24 16 4.5 - -	4 49.5

813. *A needle first balanced horizontally on its center of gravity and then magnetised, no longer retains its level, but its north pole spontaneously takes a direction to a point below the horizon called the* DIP OF THE NEEDLE.

* Library of Useful Knowledge.

† Dr. Bowditch, however, found in the diurnal variation at Salem, Mass. in the year 1810, that the declination varied, in a short period of time, 48′.

Fig. 240.

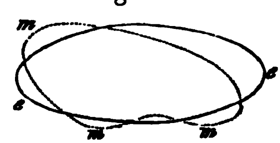


The *Dipping Needle*, is represented in figure 240. When used it is to be placed in the magnetic meridian, and to render the stand which supports it, perfectly level, by means of the adjusting screws attached.

The dip of the needle is very different in different parts of the globe, being in general least in the equatorial and greatest in the polar regions. At certain places on the globe the needle has no dip, that is, becomes perfectly horizontal, and a line uniting all such places is called the *magnetic equator of the earth.* Again, in the Polar Regions, the dipping needle sometimes becomes nearly perpendicular to the horizon. In the middle latitudes, the dip is greater or less but does not correspond exactly to the latitudes.

If the magnetic meridian coincided with the geographical, the magnetic equator would coincide with the earth's equator; but such is not the fact. We may consider the magnetic equator, in general, as a great circle encompassing the earth and inclined to its equator at an angle of about 12 degrees. It not only crosses the equator at two points diametrically opposite to each other, as a regular great circle would do, but crosses it also in one or perhaps two intermediate points, as is represented by the dotted line in figure 240.

Fig. 241.



The dip of the needle, like the declination is not constant at the same place, but undergoes a slight variation from year to year. In the course of two hundred and forty five years it has varied at London more than 5°. Its present amount is about 70°, and the variation is from two to three minutes annually.

814. *The force exerted by the magnetism of the earth varies in different places: its comparative estimate for any given place, is called the* MAGNETIC INTENSITY *for that place.*

As in the case of the pendulum in its relation to the force of gravity, the magnetic intensity may be measured by the *number of oscil-*

lations, (Art. 255.) which a needle drawn a given number of degrees from its point of rest, performs in a certain time, as a minute for example, the force being as the square of the number of oscillations. In general it is well ascertained that the magnetic intensity is least in the equatorial regions and increases, as we advance towards the poles. It is probably at its maximum at the magnetic poles. By ascertaining, from actual observation, a number of different places on the surface of the earth where the magnetic intensities are equal, and connecting them by a line, it appears that they arrange themselves in a curve around the magnetic pole. These lines are called *isodynamic curves*. Extensive journeys, have been undertaken by Humboldt, Sabine, Hansteen, and others, to ascertain the point on the surface of the earth where the magnetic intensities are equal, for the purposes of describing these curves. The earlier results indicated the position of the magnetic pole to be in the northeastern part of Hudson's Bay, lat. 60° N. lon. 80° W.;* but the directions of these curves presented such anomalies as to suggest the idea of a second magnetic pole in the opposite hemisphere, with the view of ascertaining this point, Professor Hansteen of Christiana several years since, undertook a journey into Siberia, at the expense of the King of Sweden, and has fully confirmed the fact, that there exists a second magnetic pole to the north of Siberia, around which the isodynamic curves arrange themselves in regular order.† From experiments made in deep mines and in the upper regions of the atmosphere by aëronauts, it appears that in both these situations, the magnetic intensity is the same as at the corresponding places on the surface of the earth.

815. *The effects produced by the earth on a magnetic needle, correspond to those produced on it by a powerful magnet, and hence the earth itself may be considered as such a magnet.*

The magnetism of the earth has been supposed by some to result, from a great magnet lying in the central parts of the earth;‡ by

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* Capt. Parry fixes the place of the magnetic pole in 102° W. lon. and 73° N. lat. † *Sabine*, Amer. Jour. XVII, 145. ‡ Gilbert.

others,* to be nothing more than the *resultant* of all the smaller magnetic forces scattered through various parts of the terrestrial sphere; and by others, to be excited on the surface of the earth by the action of the solar rays.

The supposition of a great magnet in the interior of the earth, to which all the phenomena of terrestrial magnetism are to be ascribed, is the earliest hypothesis, and is adequate to explain most of the facts of the science. But such a supposition is inconsistent with the recent discovery of two north poles (Art. 815.) implying the existence of four magnetic poles of the earth. The opinion of Biot, that terrestrial magnetism is only the aggregate, or resultant, of all the individual magnetic forces residing in different parts of the earth, appears to be no improbable supposition, and accords well with the general doctrine of the composition of forces.

816. The question has been raised, whether the magnetism of the earth is of the same nature with that induced upon simple iron, or whether it is of the nature of permanent magnetism. The two kinds are distinguishable from each other by the position which the centers of magnetic action have. In a ball or shell for example, of simple iron, the center of action is coincident with the center of attraction of the mass; but when the ball is rendered a permanent magnet, those centers of action, or poles, are in the surface of the body. Are we then to consider the two poles or centers of action which give direction to a magnetized needle on the surface of the earth, as coincident in the center of the earth, or as at the extremities of that diameter which may be called the polarizing axis of the earth? Till very lately, no doubt was ever entertained, that the magnetic poles of the earth were either on, or very near its surface, in points nearly diametrically opposite to each other, one within each frigid zone; and that to those poles (which have been increased from two to three, four, or more, according to the particular views of the respective authors) the needle owed the directive quality which has for many centuries so much exercised the talents and ingenuity of philosophers.

At length, however, in this, as in other branches of philosophy, the habit arose of registering facts and observations; and then it was

* Humboldt and Biot.

found to be impossible to assume any situation for these centers near the terrestrial surface, that would lead to results corresponding to those obtained from the observations which had been recorded. Another mode of proceeding was therefore adopted, viz. the situation of the two centers was now treated as indeterminate; and then by a comparison of the general analytical expression thus obtained, with experiment, philosophers endeavored to ascertain the actual situation of the poles in question. M. Biot was the first to examine the subject under this point of view; and, after numerous comparisons, he at length decided that the nearer the poles were assumed towards each other, the nearer the computed and observed results agreed; and finally, by assuming the two centers as indefinitely near to each other in the center of the earth, the two series of numbers as obtained from those two sources, approached as nearly to complete coincidence as could possibly be expected. It follows therefore that the laws of terrestrial magnetism are not to be sought among those which belong to bodies permanently magnetic, but to those appertaining to bodies passively or temporarily magnetic, as for example, simple iron and other ferruginous masses.*

817. In the year 1813, Dr. Morichini, of Rome, announced that the violet rays of the solar spectrum have the property of rendering iron magnetic. In 1825, these experiments were repeated and extended by Mrs. Somerville† and resulted in proving that the magnetizing power is not confined to the violet rays, but extends to the indigo, blue, and green rays. The probable conclusion is, that a class of rays emanate from the sun which have the property of producing magnetism and are distinct from those which afford light and heat, and produce chemical changes. Hence in the solar beam there are at least four distinct tints of rays, denominated, respectively, *colorific, calorific, chemical, and magnetizing* rays.‡

818. *Electricity and magnetism are, in some of their properties, remarkably alike, but in others strikingly dissimilar.*

Several of these analogies have been already incidentally mentioned; but it will be useful to the student to consider them in connec-

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* Barlow. † Phil. Trans. 1826. ‡ See Brewster's Optics, p. 92.

tion. Electricity and magnetism agree in the following particulars: (1.) Each consists of two species, the vitreous and resinous electricities, and the austral and boreal magnetisms. (2.) In both cases, those of the same name repel, and those of opposite names attract each other. (3.) The laws of induction in both are very analogous. (4.) The force, in each, varies inversely as the square of the distance. (5.) The power, in both cases, resides at the surface of bodies, and is independent of their mass.

But electricity and magnetism are as remarkably unlike in the following particulars. (1.) Electricity is capable of being excited in all bodies and of being imparted to all: magnetism resides almost exclusively in iron in its different forms, and, with a few exceptions, cannot be excited in any other than ferruginous bodies. (2.) Electricity may be *transferred* from one body to another: magnetism is incapable of such transference; magnets communicate their properties merely by *induction*, a process in which no portion of the fluid is withdrawn from the magnetizing body. (3.) When a body of elongated figure is electrified by induction, on being divided near the middle, the two parts possess respectively the kind of electricity only which each had before the separation; but when a bar of steel or a needle magnetized by induction, is broken into any number of parts, each part has both polarities and becomes a perfect magnet. (4.) The directive properties and the various consequences that result from it, the declination, annual and diurnal variations, the dip, and the different intensities in different parts of the earth, are all peculiar to the magnet and do not appertain to electrified bodies.

819. *The phenomena of magnetism are explained on the hypothesis of two fluids, residing naturally in iron and all ferruginous bodies, which when united, exactly neutralize each other's effects, but which, when separated, exhibit the respective properties of boreal and austral magnetism.*

Nearly all the arguments alleged in favor of the hypothesis of two fluids in electricity, apply equally well to magnetism. It is necessary however to assume, that the two magnetic fluids are separated from each other only at distances extremely small, for otherwise it is impossible to account for the fact, that when a magnet is divided into

minute fragments, each piece contains both fluids, being a perfect magnet with two opposite poles. (Art. 803.) This hypothesis, like the corresponding one in electricity, has been submitted by Poisson to to the most rigorous mathematical analysis, and all the deductions made from it are found to accord exactly with the facts as ascertained by experiment. Hence this doctrine is generally received, and has nearly superseded the explanation formerly given by Æpinus, who accounted for magnetic phenomena on the supposition of a single fluid, similar to the Franklinian hypothesis of electricity.

According to the foregoing hypothesis, iron differs from nearly every other natural substance in containing a certain portion of the compound magnetic fluid. This usually maintains its equilibrium and therefore is latent or insensible; but various causes disturb this state of equilibrium, and then the separate fluids exhibit their peculiar properties. When once separated, they have the power of producing on the magnetic fluid of other masses of iron a similar separation, each repelling the similar and attracting the dissimilar species. Hence one magnet affords the means of making another, and the process of magnetizing consists not in imparting any thing from the magnetizing body, but merely in decomposing the fluid before residing in the body magnetized, that is, separating it into its constituent fluids. Indeed, so far from losing by the process of magnetizing, the original magnet itself gains by the re-action of the new magnet which it has formed, which tends still more fully to develope or separate its own constituent fluids. By this means, what was originally a very weak, may become a strong and powerful magnet, without any other aid, than what contributes to separate more fully the two fluids naturally inherent in it.

820. The facility with which soft iron acquires and loses magnetism, (Art. 800.) is conceived to depend on the ease with which the magnetic fluids pervade a mass of loose texture in which the particles have comparative freedom of motion, while the greater fixedness of the particles of hard steel, creates an obstruction to the motions of the same fluids. Thus a magnet loses its powers by exposure to a white heat, (Art. 802.) because the separate fluids having freedom of motion combine and neutralize each other; and the method of imparting magnetism to iron by magnetizing it while softened by heat and

suddenly cooling it, is so effectual, because in this way the two fluids are first easily separated by induction, and prevented from combining by the increased obstruction created by hardening the metal. The development of magnetism in an iron bar by percussion, (Art. 801.) is supposed to be owing likewise to the greater freedom of motion to the magnetic fluids by the vibration of the particles of iron, thus enabling these fluids to separate from one another, while as soon as the vibration ceases, that freedom of motion is lost, and the fluids are prevented from reuniting. That such a vibration is favorable to the effect produced is inferred from the fact that blows which produce a *ringing* sound are peculiarly efficacious in developing magnetism. The same explanation is applied to the case where magnetism is lost by percussion; since here, the vibration would enable the separate fluids to combine.

The periodical changes in the situation of the magnetic poles of the earth upon which the direction of the needle depends, including the annual and diurnal variations, the dip, and the intensity of the force, result from causes which have hitherto eluded discovery.

Methods of making Artificial Magnets.

821. If the learner has made himself acquainted with the principles expounded in the preceding propositions, he will be qualified to proceed, with interest and intelligence, to an explanation of the leading methods practised in the manufacture of artificial magnets. These methods also, by involving a practical application of those principles, will serve to impress them on the memory and to render the knowledge of them familiar.

It will be recollected that magnets are made from other magnets; that this is done not by any *transference* of a portion of the power of the magnetizing body, but by the development of the powers naturally residing in the body to be magnetized; that this development is effected wholly on the principle of induction; that the original magnet gains instead of losing by its action on other bodies; that this power may be induced on iron by the agency of an artificial magnet, or of the loadstone, or of the earth which is itself a weak magnet, and acts upon the same principles as any other magnet. It must also be kept clearly in mind, that soft iron or steel readily ac-

quires and as readily loses the magnetism induced upon it, and that hardened iron or steel receives it slowly and with much difficulty but retains it permanently. As the earth itself may be supposed to have been the original source of magnetism in all other bodies in which it is found; we shall begin by describing the methods of magnetizing from the earth without the aid of either a loadstone or an artificial magnet.

822. *A certain degree of magnetism may be given to steel bars by hammering them while in a vertical position.*

Bars of steel prepared for this purpose are of a prismatic form with rectangular sides, the length being ten times the breadth, and twenty times the thickness. Six or eight bars of equal size are to be provided, and being held in a vertical position they are to be struck with a few blows of the hammer, when they will be found to have acquired a feeble degree of magnetism, which is indicated by their exhibiting polarity and having the power of attracting iron filings. This effect will be much greater if the bars, while receiving the blows, be placed near to a mass of iron, so as to experience its inductive influence. A pair of tongs may be used for this purpose; during the process the tongs themselves become magnetic and by their reaction greatly increase the magnetism of the bars.

823. *A needle may be magnetized by simply suffering it to remain in contact with the pole of a strong magnet; or better between the opposite poles of two magnets.*

The effect produced by two magnets is much more than double that of one magnet as may be inferred from article 796. But if the needle be of considerable length, several intermediate sets of poles are sometimes developed, as will be seen by applying iron filings. It adds much to the power of the two magnetic bars between which the needle is placed, if to the extremity of the bar most remote from the needle, a mass of soft iron is placed. (See Art. 797.) The iron in this case, acts and reacts by induction; and hence whenever magnets are not in use, they require to be connected with iron to prevent the loss of their powers. Pieces of soft iron thus con-

nected with magnets for the purpose of augmenting their powers by induction, are called *armatures*. Thus A is the armature of the horse shoe magnet represented (Fig. 243.)

824. But it must be recollected (Art. 819.) that the two species of magnetism are not, like those of electricity separated to a distance from each other, so that one kind may be wholly collected at one end of the bar and the other kind at the other end; but that the two are separated only at a minute distance remaining in the immediate vicinity of each other throughout the whole length of the bar. Hence, in order to give the magnetizing pole its full effect, it becomes necessary to apply it successively to every part of the bar from one end to the other.

A more effectual method of magnetizing a needle is the following: Place two magnetizing bars A, B, parallel to each other, with their dissimilar poles adjacent; unite the poles at one end by a piece of soft iron R, and apply the poles at the other end to the needle, as is represented in figure 242. Upon this principle, that is, the increased energy with which the two poles act together, is formed what is called the horse shoe magnet, which derives its name from its peculiar figure, (fig. 243.) Bars of this form are converted into magnets upon the same principles as straight bars, the magnetizing bar, being made to follow the curvature always in the same direction. A very efficacious mode of making horse shoe magnets is thus described by Professor Barlow. Two horse shoe bars may be united at their ends, in such a manner that the poles which are to be of opposite names shall be in contact. They are then to be rubbed with another strong horse shoe magnet, placing the latter so that its north pole is next to the south pole of one of the new magnets, and consequently its south pole next to the north pole of the same; carrying the movable magnet round and round always in the same direction. This is esteemed one of the most eligible modes of making powerful magnets.

Fig. 242.

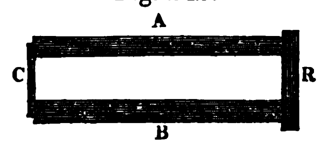
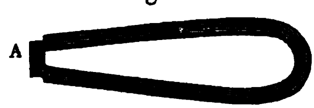


Fig. 243.



The horse shoe magnet is itself very convenient for imparting magnetism to other bodies. Place the poles near the center of the needle; move them along its surface backwards and forwards, taking care to pass over each half of it an equal number of times; repeat the same operation on the other side; and the needle will become speedily and effectually magnetized.

825. The best mode of making magnetic needles in general, is expressed in the following rule, given, as, the result of very extensive and accurate experiments by Capt. Kater.

*Place the needle in the magnetic meridian; join the opposite poles of a pair of bar magnets, (the magnets being in the same line) and lay the magnets so joined, flat upon the needle, with their poles upon its center; then having elevated the distant extremities of the magnets, so that they may form an angle of about two or three degrees with the needle, draw them from the center of the needle to the extremities, carefully preserving the same inclination; and having joined the poles of the magnets at a distance from the needle, repeat the operation ten or twelve times on each surface.**

In connexion with the foregoing rule Capt. Kater gives the following summary of principles established with respect to the compass needle. 1. That the best *material* for compass needles is a clock spring; but care must be taken, in forming the needle, to expose it as seldom as possible to heat, otherwise its capability of receiving magnetism will be much diminished. 2. That the best *form* of a compass needle is a pierced rhombus, (fig. 245.) in the proportion of about five inches in length to two in width, this form being found susceptible of the greatest directive force. 3. That the best method of tempering is first to harden the needle at a red heat, and then to soften it from the middle to about an inch from each extremity, by exposing it to heat sufficient to cause the blue color which arises, again to disappear. 4. That in the same plate of steel of the size of a few square inches only, portions are found *varying considerably in their capability of receiving magnetism*, though not apparently differing in any other respect. 5. That *polishing* the needle has no

* Phil. Trans.

apparent effect on its magnetism. 6. That in needles from five to eight inches in length, their weights being equal, *the directive forces are nearly as the lengths.* 7. That the directive force does not depend upon extent of surface, but, in needles of the same length and form, it is as the *mass.* 8. That the deviations of a compass needle, occasioned by the attraction of soft iron, depends on *extent of surface* and is wholly independent of the mass, except a certain thickness of iron, amounting to about two tenths of an inch, which is requisite for the complete development of its attractive energy.

826. The reasons on which the preceding rule and the annexed principles are founded, will for the most part be understood from what has gone before. A needle to be magnetized is placed in the magnetic meridian, because (the earth being considered as a magnet) the needle has its axis then parallel to that of the magnet, a position in which (Art. 797.) it receives the greatest effect from induction. The opposite poles are joined, because acting reciprocally upon each other by induction, they augment each other's powers. The bars thus joined are placed on the center of the needle and drawn in opposite directions, for, by this means, upon that part of the needle which lies between them, the action of the two poles conspire. Upon the part which lies between each bar and the adjacent extremity of the needle, the influence of the two poles is indeed opposed to each other; but as the poles are more remote from the parts where their actions oppose each other than from the parts where their actions conspire, they on the whole tend to augment each other's effects. The bars are first laid flat wise, and afterwards elevated by as small an angle as will serve the purpose of drawing them asunder, with their poles only in contact with the needle, because (Art. 797.) the effect of induction is strongest when the magnetizing bars are nearest to a parallelism with the body to be magnetized; and the same angle of inclination is carefully preserved, for it is only in this way that both sides of the needle will have precisely the same strength, a condition essential to its perfection. In renewing the application of the bars they are removed to a distance before their poles are joined again, because it is important to secure the magnetism the needle has already acquired against those partial disturbances which might arise from the irregular action of the magnetic bar.

827. It may be observed, moreover, that in addition to these rules for communicating magnetism to the needle which are derived from general principles, there are others more or less empirical, which are derived from experiments expressly instituted for ascertaining all the circumstances most favorable for giving perfection to this important instrument. Coulomb devoted himself, with his wonted assiduity, to researches of this kind, with the view of ascertaining the kind of steel best suited to compass needles; the size, form, and the temper, that are most advantageous; and the comparative merits of the different methods of magnetizing. By suspending the needle operated on in the place of the revolving index of the Torsion Balance, (fig. 123.) he had a most delicate test of the degree of attraction and directive force acquired in all the different cases which can be supposed to influence the powers of the needle. Capt. Kater has recently followed in similar inquiries; and it is from the results of his own and all other similar investigations, that the principles above specified are compiled.

828. *Magnets are liable to lose their power, to prevent which certain precautions are necessary.*

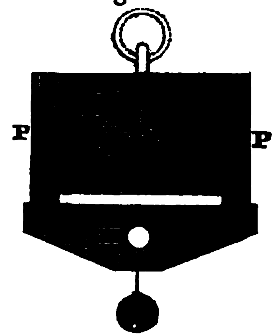
If a single magnet is kept out of its natural direction it grows gradually weaker, and this loss of power is most rapid when its position is the reverse of the natural one, that is, when its north pole is turned towards the south. Under these circumstances, indeed, unless the magnet is made of the hardest steel, it will in no long time lose the whole of its magnetic power. Two magnets may also very much weaken each other if they be kept even for a short time, with their similar poles fronting each other. The polarity of the weaker magnet, especially, is rapidly impaired, and some times found to be actually reversed. More frequently, however, there arises, from this opposition of powers, considerable irregularity and confusion in the poles of both magnets.

Since heat also impairs the powers of the magnet (Art. 802.) it should never be exposed to a high temperature. We should likewise be very cautious to avoid all rough and violent treatment; for its virtues are speedily impaired by concussion or whatever occasions a vi-

bration among its particles. It must not therefore be suffered to fall on the floor, or be rubbed with coarse powders, or be ground with the view of altering its form. The loadstone has its powers impaired by similar means; hence we should attempt to alter its natural form as little as possible; and when it is necessary to do so, it should be effected very rapidly by cutting it on a lapidary's wheel.

Although the loadstone retains its magnetic virtue more tenaciously than any artificial magnet that can be constructed, yet even this body requires a certain management for the permanent preservation of its powers. For this purpose it should be *armed*, as it is called; that is, a piece of soft iron should be kept constantly in contact with the two poles. In order to do this most effectually, we must first ascertain the situation of the poles of the loadstone; and cutting off all the superfluous parts, give it the shape of a parallelopiped, having the poles in the middle of two opposite surfaces, and at the same time taking care to preserve the axis, which passes through the poles, of as great a length as can be obtained; for it has been observed, that any curtailment of the magnet in the direction of this line, deprives it of force in a greater degree than when shortened in any other direction. Plates of soft iron are next attached to the two sides containing the poles, which are made to project a little way below the bottom of the loadstone, terminating in two bars like the poles of a horse shoe magnet, to which bars a short bar of soft iron is attached, upon which the whole force of both poles acts simultaneously. This action exerted upon the iron bar is sufficient to preserve the powers of the loadstone from decay, (see fig. 244.) A similar piece of iron is applied by way of armature, to the two poles of a horse shoe magnet. Bar magnets also, when laid aside, should be placed with the north pole of one in contact with the south pole of another, or what is better, two bars may be placed parallel, at a little distance from each other, with their like poles in opposite directions, and having their dissimilar poles united by short pieces of iron,

Fig. 244.

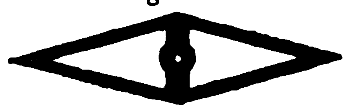


so as to form with the bars a parallelogram. Magnets should be polished because they are then less liable to contract rust.*

The Compass.

829. The Compass, (the importance of which to mankind, has attached to the subject of magnetism its principal value,) is of many different forms, but the chief varieties are the land compass, the Mariner's compass, the Azimuth compass, and the Variation compass. The needle, in all these varieties, is usually a thin flat plate of steel, tapering at the extremities; but, as we have already mentioned, (Art. 825.) a more eligible form has been proposed by Capt. Kater, consisting of four narrow strips of steel, united in the form of a hollow rhombus, (fig. 245.) It is found advantageous to concentrate the powers of the needle as much as possible in the two extremities, and to avoid all inequalities, arising from intermediate poles, or from a difference of strength in different parts. The needle is secured at the point of suspension, and furnished with a conical cap of brass which rests on a perpendicular pin; and still farther to diminish friction, the point which rests on the extremity of the pin, is made of agate, one of the hardest mineral substances. Since, if the needle is magnetized after having been balanced on its center of gravity, it would no longer remain horizontal, the equipoise is restored by attaching a small weight to the elevated side.

Fig. 245.



830. The compass, in its simplest form, consists of a needle like the foregoing enclosed in a suitable box covered with glass. This is all that is essential when it is required merely to know the direction of the meridian, or the north and south points. But, for most purposes, the compass is furnished with a graduated circular card, divided into degrees and minutes; and in the mariner's compass the card is also divided into thirty two equal parts called rhumbs. The card thus divided is fastened to the needle itself, and turns with it.

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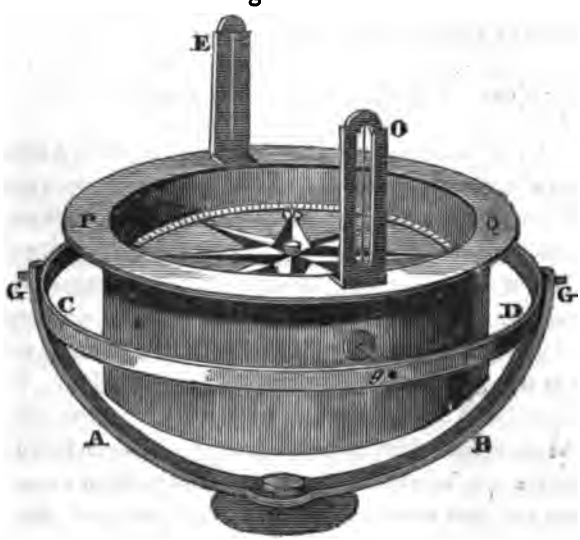
* Lib. Useful Knowledge, *Magnetism*, p. 54.

831. Thin, slender needles have the greatest directive powers, and are most sensible, since they undergo less friction than those which are heavier, but due regard to strength requires them to be made of a certain degree of thickness; an increase of length is attended with an increase of directive power; but when the thickness remains the same, the weight, and consequently the friction, increases in the very same ratio; no advantage, therefore, as to directive power can be obtained by any increase of length. Moreover, needles which exceed a very moderate length, are liable to have several sets of poles, a circumstance which is attended with a great diminution of directive force. On this account, short needles, made exceedingly hard, are generally preferable.

Fig. 246.



832. The great importance of the mariner's compass, has made its construction an object of much attention, and the best artists have tried their skill upon it. The compass is suspended in its box in such a manner as to remain in a horizontal position notwithstanding all the motions of the ship. This is effected by means of *gimbals*. This contrivance consists of a hoop, usually of brass, (fig. 246,) fastened horizontally to the box by two pivots placed opposite to each other, and constituting the axis on which the hoop turns up and down. At an equal

distance from the pivots on each side, that is, at the distance of 90° from each pivot, two other pivots are attached to the ring at right angles to the former, on which the inner box that contains the card is hung. Of course when it turns on these pivots, its motion is at right angles with that of the hoop. Therefore all the motions of which the compass box is capable, are performed around two axes which intersect each other at right angles; consequently the point of intersection, being in both axes, will not move at all. But the needle and the attached card rest upon this point, and are connected with the compass box in no other point. Hence they remain constantly horizontal in every position of the box.

The Azimuth compass* differs from the common mariner's compass only in having sights attached, by which the bearing of any object with the meridian may be ascertained. The Surveyor's compass is a variety of the azimuth compass.

Local Attraction of vessels.

833. A few years since it was observed, for the first time, that the needle of the mariner's compass on board of a ship, does not continue to point constantly in the same direction, but alters its direction as the ship heads towards different parts. Changing the position of the ship from north or south to east or west, sometimes changes the direction of the needle 20° or 30°. Indeed, in one instance mentioned by Capt. Sabine, shifting the ship's head from east to west, produced a change in the direction of the needle amounting to 50°. Such irregularities are found to be greatest in the polar seas. This effect is caused by the attraction which the large quantity of iron on board a ship exerts upon the needle, consisting of the guns on board of a man of war, of the masses of iron sometimes employed as ballast, of the iron tanks recently substituted for water casks, and of the various bolts, bars, nails, &c. which enter more or less into the construction of every sort of vessel.

In order to investigate the laws by which these effects were controlled and to devise a remedy for them, Professor Barlow, of the

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* *Azimuth* as applied to a star or any celestial object, is an arc of the horizon intercepted between the meridian and a vertical circle passing through the object.

Military Academy of Woolwich, instituted a great number of experiments which resulted in the discovery of a method of obviating completely every difficulty by neutralizing the effect of the iron of the ship, and leaving the needle free to obey the impulse of terrestrial magnetism alone. It is easy to understand that all the various forces exerted by the iron in different parts of the vessel will have a single *resultant* equivalent to the whole; and that, if we can discover the amount and direction of this resultant, it will be only necessary to apply an equivalent force in the opposite direction to neutralize the effect of the iron.

834. Mr. Barlow procured a solid ball of iron thirteen inches in diameter, and two hundred and eighteen pounds in weight. When the compass was *above* the ball, he found that the north end of the needle was attracted towards it; and that when it was *below* the ball, the south end was attracted towards it; and that in traversing the interval between these two positions, it always passed through a point in which the ball had no effect on the needle. Instead however of moving the compass through these different positions, the compass was suffered to remain stationary, and the ball suspended by means of pulleys was raised or lowered at pleasure, and thus easily brought into any required position with respect to the compass. The experiments showed that all those points in which the ball exerts no influence on the needle, are in the same plane, and that this plane is inclined to the horizon towards the south, making an angle with the horizon equal to the complement of the dip; and of course the direction of this plane is at right angles to the direction of the dip. This plane, therefore, in reference to the iron sphere, constitutes its magnetic equator. It is at right angles to the magnetic meridian and cuts the horizon in the magnetic east and west points. A compass needle whose center is anywhere in this plane will not have its action disturbed in the least by the influence of the ball. Hence this plane is denominated the *plane of no attraction* or the plane of neutrality. Nor is the existence of such a plane confined to masses of iron of a globular shape; it extends equally to masses of the most irregular form, and even to an assemblage of detached masses like those disposed through different parts of a ship.

835. The actual amount of deviation produced in the ship's compass by its local attraction will, of course, be different in different vessels. With an easterly or westerly course, it has been observed in the latitude of London to vary from five to twelve or fourteen degrees: it is of greater amount as the ship is in higher latitudes; and diminishes, without vanishing, at the equator; and again increases as we approach the south pole. Experiments were made on eight different men of war in the British harbors, and in all of them very considerable deviations were detected from the local cause under consideration, and an average deviation in the whole of $8^{\circ} 44'$. The Gloucester, one of these ships, was invariably drawn to the southward of her intended place, notwithstanding the greatest care was taken in steering her. Had it not been ascertained, by taking an observation that this error was altogether the effect of local attraction, it would probably have been ascribed to the influence of an unknown current. The real deviation, estimated in distance, would occasion the vessel, after running ten miles, to be more than a mile and a half to the southward of her reckoning, and so on as the distance increased. An error of this magnitude, occurring in a narrow channel, and in a dark night, were it unknown or disregarded, might lead to the most disastrous consequences; and shipwrecks have been traced with much probability to this source of error in the reckoning. The loss of the Thames Indiaman a few years since was ascribed to this cause. This vessel besides the usual supply of guns, had a cargo of more than four hundred tons of iron and steel. The influence of such an enormous magnetic mass would alone be quite sufficient to explain the otherwise unaccountable circumstance, that after leaving Beachey head in sight at six o' clock in the evening, the ship was wrecked upon the same spot between one and two o'clock in the morning, without the least apprehension of being near the shore.*

* Barlow.

Fig. 246.

836. The *Correcting Plate* of Professor Barlow affords an effectual remedyf or those errors. It consists of a double plate formed of two thin disks of iron, screwed together in such a manner as to combine any strong irregular power of one plate, with a corresponding weak part of another; by which means a more uniform action is obtained. These plates are of a circular form twelve or thirteen inches in diameter. Now, it being ascertained from actual experiment (comparing the direction of the compass on board with its direction on the shore), what is the amount of deviation occasioned by the iron of the sbip, it is evidently possible by bringing a small quantity of iron *near* to the needle to produce in it a deviation of the same amount, and of course to double the error in question. The point where the correcting plate must be placed in order to produce this effect may be ascertained by experiment, and the plate afterwards laid aside. Whenever it is required to determine the error of the needle, the plate is restored to its place, the deviation it occasions in the needle noted, which is equal to the error sought. Or, the plate may be fixed permanently on the other side of the needle in such a manner as easily to neutralize the error, leaving the needle subject to the attraction of terrestrial magnetism alone.

In order to bring the efficacy of the correcting plate to the test of experience, several of the ships of the Royal Navy of Great Britain were furnished with it, and trials were instituted with it in various parts of the world from the arctic to the antarctic circle, and with the most satisfactory results. This expedient, therefore, is at present held to be a most effectual corrective of the errors from the local attraction of vessels.

837. Chronometers, also, which are carried on board of ships for the purpose of finding the longitude, are liable to have their rate of going affected by the magnetic action of the iron of the ship. Although a sudden alteration in the rates of chronometers at sea, had frequently been observed, yet the cause was not detected until as late as the year 1818. It appeared on examination, that the effect was produced by the magnetic action of the ship's iron upon the in-

ner rim of the balance of the chronometer, which is made of steel. A similar influence was perceptible on placing magnets in the neighborhood of the chronometer. Mr. Barlow applied himself to experiments on this subject, and found that masses of iron wholly destitute of permanent magnetism, occasioned an alteration in the rates of chronometers, placed near them in different positions. Sometimes they were accelerated and sometimes retarded. Hence, it is recommended to keep the chronometer, on board of any ship, out of the vicinity of any large mass or surface of iron.

The method proposed for rectifying this error is the same as that for correcting the compass, namely, by first ascertaining what the effect of the ship's iron upon the chronometer is, and then applying the correcting plate upon the same principles as in the case of the compass. The late voyages to the northern seas, undertaken by the British government, however they may have failed of gaining their principal object, namely, the discovery of a northwest passage, still achieved many valuable results in experimental science, but in none perhaps more than in the science of magnetism. Among the rest, they made numerous observations on the local attraction of vessels; on the magnetic effect of the ship's iron upon the rate of chronometers; upon the position of the magnetic poles; upon the phenomena of the dipping needle; and upon the magnetic intensities of different places on the earth's surface.

Magnetic Charts.

838. The great importance of the mariner's compass to the art of navigation, has induced the British government, at different times, to send abroad men of science to make observations on magnetism in different countries, with the view of reducing the principles on which the variation of the compass depends to settled laws. The first great enterprise of this kind was undertaken about the year 1680, by Dr. Halley, one of the most distinguished and zealous philosophers of that age. For the purpose of ascertaining the law of the variation of the compass, Dr. Halley was invested with the command of a national ship, in which he traversed the Atlantic ocean in various parts, extended his voyage to the fiftieth degree of south latitude. After he had collected a great number of observations made by others, and com-

pared them with his own, he published, in the year 1700, a synopsis of them in the form of a chart, in which the ocean was represented as crossed by a number of lines passing through those places where the compass had the same deviation. Thus, in every point of one line there was, in the year 1701, no variation; in any point of another line, the compass had twenty degrees of east variation; and in every point of a third line it had twenty degrees of west variation.*

But, though Halley's chart was constructed with all possible care, and presented a comprehensive view of all that was then known of the subject, yet it could not be of much permanent utility since the lines of which it is composed are themselves continually changing their relation to one another. Among the recent Magnetic Charts which have been published, that of Professor Hansteen of Norway is the most extensive and most useful.†

The great and constant irregularities of all the lines described on magnetic charts, whether they relate to the variation of the compass, or to the magnetic dip and intensity, are such as almost to preclude the hope of reducing the phenomena of terrestrial magnetism to laws so definite, as to afford rules of calculating these particulars for any given place, independently of experiment. The western line of no variation, however, is much more regular than the eastern; and a general idea may be formed of it, by conceiving it to extend from a point to the northwest of Hudson's Bay, running in a southeasterly direction through the western part of Lake Superior, and through Lake Michigan, passing near the western extremity of Lake Erie, and through North Carolina. It runs not far from the Island of Bermuda, and thence, eastward of all the West India Islands to the northwestern part of South America, near the equator. Thence its course is through the Southern Atlantic to the longitude of Greenwich. Such, however, is the variation of the compass, that Professor Barlow is of the opinion that every place has a polarising axis peculiar to itself, and that it is vain to seek for magnetic poles common to the whole earth.

* Robinson's Mech. Phil. IV, 358.

† See an excellent representation of this chart in the Encyclopædia Metropolitana, Art. *Magnetism*.

PART VI.—OPTICS.

CHAPTER I.

PRELIMINARY DEFINITIONS AND OBSERVATIONS.

839. Optics *is that branch of Natural Philosophy which treats of Light and Vision.*

More particularly, it is the object of this science to investigate the *nature* of the agent on which the phenomena of vision depend; to treat of the *motions* of light, in respect to its direction, its velocity, and its reflexion from the surfaces of bodies, to trace its change of direction, and the various other modifications it undergoes by passing through different transparent media; to explain the *phenomena of nature* which depend upon the properties of light, embracing the doctrine of *color;* to trace the relation between light and the structure of the eye, comprehending the subject of *vision;* and finally, to describe the various *instruments* to which a knowledge of the principles of Optics has given birth, disclosing many new and wonderful properties of light, and extending the range of human vision, on the one hand, to myriads of objects too minute, and on the other, to numberless worlds too remote, to be seen by the unassisted eye.

840. "There is no branch of Philosophy (says the Abbe Haüy) more deserving of our study, whether we consider its beauty, or the multitude of phenomena which it exhibits. The advantages we derive from the fluid that enlightens us are sufficient of themselves to excite the closest attention, that we may fully understand its properties. If air, serving as the vehicle of speech, enables us to carry on an intercourse of thought with our fellow creatures, how greatly is that intercourse improved by light, which renders their image present to us,—their image which has so many things to say! The eye, more susceptible than any of the other senses of multifarious impres-

sions, by the aid of light, takes in at once, in bodies, the forms by which they are limited, the colors that embellish them, their relative positions, and the motions by which they are transported in space. It discriminates, without confusion, all those modifications that seem to sport in a thousand different ways, in that grand diversity of objects to which a single look can extend itself."

841. To these remarks it may be added that, the greatest minds have labored here; the genius of Newton has left its impress upon every part of this science; an agent, the most subtle and fleeting in nature, has, by such hands, been bound down to the most rigorous mathematical laws; and since Optics lays the foundation for the most curious as well as the most sublime researches in nature, in the two provinces of Natural History and Astronomy, men of the most profound and ingenious minds, in different countries, have labored and are still laboring to carry it to perfection. With a view of securing to the learner the greatest practical advantages from the study of this science, we shall select for his perusal, from the vast mass of materials that have been accumulated and which are to be found in optical writers, such principles and such illustrations, as we shall deem most instructive in regard to the properties of light and colors, and the principles of vision, and to the construction of such instruments as mirrors, microscopes and telescopes. Our limits will necessarily compel us to omit the detail of many interesting and curious modern researches into the nature of light and colors, for the development of which we must refer to more extensive treatises, as those of Biot, Brewster, Herschel and Coddington.

842. Luminous bodies are naturally of two kinds, such as shine by their own light, as a lamp or the sun, and such as shine by borrowed light, as the moon, and most of the visible objects in nature.

A *ray* is a line of light; or it is the line which may be conceived to be described by a particle of light. In a more general sense, the term is applied to denote the smallest portion of light which can be separately subjected to experiment. A *beam* is a collection of parallel rays. A *pencil* is a collection of converging or diverging rays. A *medium* is any space through which light passes. When a space is a perfect void, so as to offer no obstruction to the passage of light,

it is said to be a *free medium;* when the space intercepts a portion only of the light, it constitutes a *transparent medium.* Transparency, however, may exist in different degrees. When the medium itself is invisible, as portions of air, it is said to be *perfectly* transparent; when the medium is visible, but objects are seen distinctly through it, as in the clearest specimens of glass and crystals, it is said to be, simply, *transparent;* when objects are indistinctly seen through it, it is *semi-transparent;* and when a mere glimmering of light passes through, without representing the figure of objects, it is *translucent.* Bodies that transmit no light are said to be *opake.*

843. *Rays of light, while they continue in the same uniform medium, proceed in straight lines.*

For objects cannot be seen through bent tubes; the shadows of bodies are terminated by straight lines; and all the conclusions drawn from this supposition, are found by experience to be true. If two bodies with plane surfaces, as two disks of metal, be held between the eye and some luminous point, as a star, on bringing the two planes gradually towards each other, the star may be seen through the intervening space until the planes come completely into contact; but if one of the surfaces is convex and the other concave, the light is intercepted before the surfaces have met.* In consequence of the rectilinear motion of light, it forms angles, triangles, cylinders, cones, &c., and thus its affections fall within the province of geometry, the principles of which are applied with great effect to the development of the properties and laws of light, after a few fundamental properties are established by experiment.

844. From every point in a luminous object, an inconceivable number of rays of light emanate in every direction when not protected by obstacles that intercept it. Thus, from every point in the flame of a candle, as seen by night, light diffuses itself, pervading an immense sphere, and filling every part of the space so perfectly, that not the minutest point can be found destitute of some portion of its rays. Any luminous body of this kind is called a *radiant.* The

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* Biot.

pencil of light which proceeds from a radiant, is a cone, the sections of which made by any plane corresponds to the figures called conic sections. If any portion of the the pencil be intercepted by a rectilateral figure, that portion constistutes a pyramid of which the figure is the base and the luminous point itself is the vertex.

845. *Light has a progressive motion of about one hundred and ninety two thousand five hundred miles per second.*

The estimation of the velocity of light, (which may be classed among the greatest achievements of the human mind,) has been effected in two different ways. The first method is by means of the eclipses of Jupiter's satellites. To render this mode intelligible to those who have not studied astronomy, it may be premised, that the planet Jupiter is attended by four moons which revolve about their primary as our moon revolves about the earth. These small bodies are observed, by the telescope, to undergo frequent eclipses by falling into the shadow which the planet casts in a direction opposite to the sun. The exact moment when the satellite passes into the shadow, or comes out of it, as seen by a spectator on the earth, is calculated by astronomers. But sometimes the earth and Jupiter are on the same side, and sometimes on opposite sides of the sun; consequently, the earth is, in the former case, the whole diameter of its orbit, or about one hundred and ninety millions of miles nearer to Jupiter than in the latter. Now it is found by observation, that an eclipse of one of the satellites is seen about sixteen minutes and a half sooner when the earth is nearest to Jupiter, than when it is most remote from it, and consequently, the light must occupy this time in passing through the diameter of the earth's orbit, and must therefore travel at the rate of about one hundred and ninety two thousand miles per second.* Another method of estimating the velocity of light, wholly independent of the preceding, is derived from what is called the *aberration of the fixed stars*. The full explanation of this method must be referred to astronomy; but it may be understood, in general, that the apparent place of a fixed star is altered from the effect of the mo-

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* $\frac{190000000}{16.5 \times 60} = 192000$ *nearly*.

tion of its light, combined with the motion of the earth in its orbit. It will be remarked that, the place of a luminous object is determined by the direction in which its light meets the eye. But in the case of light coming from the stars, the direction is altered in consequence of the motion of the earth in its orbit, being intermediate between the actual directions of the earth and the light of the star; and the velocity of the earth in its orbit being known, that of light may be computed from the proportional part of the effect produced by it in causing the aberration. The velocity of light, as deduced from this method, comes out very nearly the same as by the other.* Hence it is inferred that the velocity of light is uniform.

846. *The phenomena of Light may be explained, either on the supposition that light is a material fluid of extreme subtility, or that it is produced by the undulations of an independent medium set in motion by the luminous body.*

Opticians of great eminence, as Descartes, Huygens, Euler, and Young, have held the opinion that light does not consist of actual emanations of material particles from the luminous body, but that such a body has merely the property of communicating a series of vibrations to a peculiar fluid that is diffused throughout the universe, which vibrations form the communication between the luminous body and the eye. The medium is conceived to be of extreme tenuity and elasticity; such, indeed, that though filling all space, it shall offer no appreciable resistance to the motions of the planets, comets, &c. capable of disturbing them in their orbits. It is moreover imagined to penetrate all bodies; but in their interior to exist in a different state of intensity and elasticity from those which belong to it in a disengaged state, and hence the refraction and reflexion of light. Newton, however, and with him the greater number of opticians have held, that light consists of actual particles of matter sent off from luminous objects to the eye. In the former case the fluid is only the medium of light, as air is the medium of sound; the vibrations of the medium following each other as wave follows wave, with incredible swiftness, and thus conveying the impression from the radiant to

* See Herschel on Light, *Encyc. Metropol.*

the eye: in the latter case, the motion is simply that of a chain of particles moving in right lines with the same astonishing velocity. Thus when the sun rises, it either sends forth luminous particles which entering the eye occasion the sensation of vision; or it puts in motion the peculiar fluid which is the medium of light, which motion is propagated from wave to wave till it reaches the eye.*

847. It forms a strong objection against the hypothesis of undulations, that the motions of light are confined to *right lines*, a condition not essential to this species of motion; while it is a strong argument in favor of the materiality of light, that it exhibits the property of attraction, one of the most characteristic properties of matter. The motion is conformable to the laws which regulate the motions of small bodies under the same circumstances. Thus, when it meets with no impediment, it moves uniformly forwards in right lines; it is affected by passing into mediums of different densities in a manner correspondent to the law of the mutual gravitation of matter, being attracted from rarer towards denser bodies; and finally it produces certain chemical changes in bodies which belong to none but a material agent. The rays of light also by passing through certain media, undergo a change to be described hereafter under the head of *polarization*, in which the opposite sides of a ray appear to be endowed with different properties, a fact which accords ill with the idea of undulations, though it is quite consistent with the doctrine of the materiality of light. The latter hypothesis moreover, has the advantage of leading the student to a more ready apprehension of the nature of optical phenomena. Still, the object of this science is not so much to ascertain the nature of the agent on which the phenomena of light depend, as it is to study those phenomena themselves, and to classify them under general laws, which may be applied to the construction of optical instruments, and to the interpretation of Nature.

848. To the doctrine of the materiality of light, it has been objected, first, that material particles endued with such immense velocity, would have a momentum which nothing could resist, much less so

* These celebrated hypotheses are stated more at large in Appendix No. I.

delicate an organ as the eye; secondly, that were the rays material, so prodigious is their number scattered throughout the universe, they would interfere with one another; aud, thirdly, that the sun and stars would waste away and grow dim, by such a constant and profuse expenditure of matter. But these objections severally admit of a satisfactory reply. In the first place, the momentum of a ray of light may still be inconsiderable, if the quantity of matter is small in the same proportion as the velocity is great. Though such an attenuation of matter is amazing, yet it is not incredible, but perfectly consistent with known analogies of nature. In the second place, notwithstanding the universal diffusion of light, no interference of its particles is necessary, for it is not essential to the purposes of vision that a ray should consist of contiguous particles of light. It is found that the sensation continues for sometime after the luminous object is removed, during an interval sufficient for light to pass through twenty two thousand miles; consequently, particles no nearer to each other than this distance, would be competent to maintain uninterrupted vision. Thus an ignited stick whirled in the air, exhibits a ring of light, because the sensation continues for a longer time than the illuminated point occupies in passing round the circle. In the third place, the small danger of waste sustained by the sun in consequence of the light which it dispenses, may be inferred from the following remarks of Dr. Priestly. After relating an experiment, in which the light of the sun collected during one second, by a concave reflector of four square feet, and thrown on the arm of a delicate balance, indicated a weight *not exceeding* the 1200 millionth part of a grain, the Doctor adds: "Now the light in the above experiment was collected from a surface of four square feet, which reflecting only about half what falls upon it, the quantity of matter contained in the rays of the sun incident upon a square foot and a half of surface in one second of time, ought to be no more than the 1200 millionth part of a grain. But the density of light at the surface of the sun is greater than at the earth in the proportion of 45000 to 1; there ought, therefore, to issue from one square foot of the sun's surface, in one second of time, in order to supply the waste by light, one forty thousandth part of a grain of matter; that is, a little more than two grains in a

day, or about 4752000 grains, which is about 670 pound avoirdupois in six thousand years."*

849. *The intensity of light, at different distances from the radiant, varies inversely as the square of the distance.*

This proposition is proved in the same manner as that respecting gravity, (Art. 11. Vol. I. p. 4.), the reasoning in which applies to all emanations from a center.

Although the intensity of light decreases rapidly as we recede from the radiant, yet the *brightness* of the object suffers little diminution by increase of distance. Thus a candle appears nearly as bright at the distance of a mile as when close to the eye. If, while the observer remains stationary, the light which was before spread over a given area, should be all collected into a space half as large, the brightness would obviously be twice as great as before; or, in general, the brightness, the quantity of light being given, is inversely as the the area, that is, inversely as the square of the diameter. Now as we recede from an object, its area is apparently diminished, and on this account its brightness is increased in the same ratio as it is diminished by the cause operating according to the foregoing proposition. The brightness therefore remains constant.†

This is to be understood, however, only of light passing through a *free medium*; by traversing the air the brightness is diminished according to the following law.

850. *The effect of a transparent medium of uniform density, is to diminish the intensity of light in a geometrical ratio.*

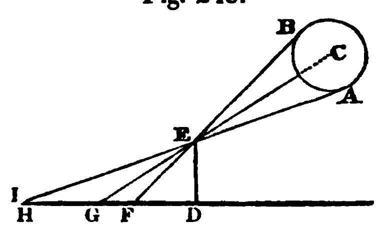
For, imagine that the medium, a piece of glass for example, is divided into equal laminæ, of such thickness that the first lamina shall stop $\frac{1}{n}$th part of the rays that fall upon it. Then there will issue from the lamina $1-\frac{1}{n}=\frac{n-1}{n}$ rays. The second lamina, in like

* Priestley, *Hist. Light and Colors.* † Herschel on Light.

manner, will stop $\frac{1}{n}$th part of the light which falls upon it, that is, $\frac{1}{n}$ of $\frac{n-1}{n}=\frac{n-1}{n^2}$. There will, therefore, issue from the second lamina, $\frac{n-1}{n}-\frac{n-1}{n^2}=\frac{(n-1)^2}{n^2}$. In the same manner it may be shown that there will issue from the third lamina, $\frac{(n-1)^3}{n^3}$. Hence the series expressing the decreasing quantities of light, is $\frac{n-1}{n}$, $\frac{(n-1)^2}{n^2}$, $\frac{(n-1)^3}{n^3}$, &c. which is evidently a series in geometrical progression.*

851. *The shadow occasioned by the interposition of an opake body, in an illuminated medium, and received on a plane, is always terminated by a penumbra or partial obscuration.*

Fig. 248.



Thus, in Fig. 248, let C represent the sun, and DE an opake body perpendicular to the horizon. The eye moving from I towards D, the light will begin to be intercepted when the eye reaches H; half the light of the sun only will be perceived at G, and beyond F, the disk will be entirely obscured.

852. *If light emanating from a luminous globe, be projected upon an opake globe that is larger than the former, the part which causes the illumination will be greater than, and the part which receives the illumination less than, a hemisphere. If the globe from which the light emanates be greater than the other, the contrary will take place. If both globes be equal, the half of the radiant globe will illuminate half of the opake globe.*

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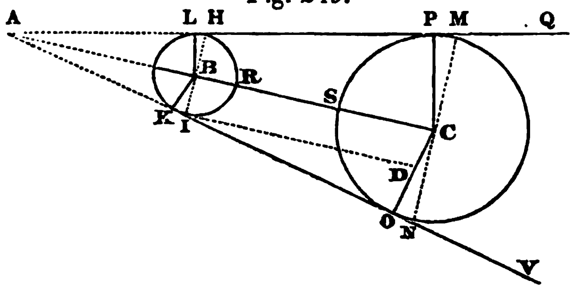
* Barlow.

Suppose that light emitted from the whole surface of the globe B (Fig. 249.) illuminates the face which is towards it of the larger globe

Fig. 249.



C; let the tangent planes, which in the figure are projected into the lines LQ, KV, be drawn to touch both spheres. Then it is evident that every part of the surface of the smaller sphere which lies between L and K towards C, communicates its portion of light towards the illumination of the larger globe; and, on the other hand, that no part of the surface of that larger globe, which is beyond the points P and O, can receive direct light from the smaller globe. If now, perpendicularly to the right line BC, which joins the centers of the two globes, there be drawn two diameters IH, NM, being projections of the great circles which divide each into its respective hemispheres, it will be manifest that the portion LRK of the smaller sphere, which illuminates the larger, exceeds a hemisphere; while the portion OSP of the larger sphere, which receives illumination, is less than a hemisphere. The contrary will obviously be the case, if C be the luminous, and B the opake globe. And if C and B were equal in size, LP and KO would both be parallel to BC; BL and BK would coincide with BH and BI; CP and CO would coincide with CM and CN: and, consequently, the portion of one globe which tended to illuminate the other, and the portion of the second which received the illumination, would both be hemispheres.

A luminous globe illuminates the half of an equal globe, at whatever distance they may be, the one from the other; but a globe which throws light upon a smaller one, illuminates so much the greater portion as it is nearer, and reciprocally.

853. The shadow of a globe that is illuminated by an equal globe, is cylindrical and indefinitely long. The shadow of a less globe, illu-

minated by a greater, (as of the earth, or of the moon, illuminated by the sun,) is a cone of finite length, whose dimensions may be easily computed when the diameters and distances of the globes are known. And lastly, the shadow of a globe, illuminated by one that is smaller, extends itself indefinitely in a truncated cone, perpetually enlarging. These several truths will be readily understood by referring to Fig. 249.*

854. Light, when it impinges on smooth surfaces, is *reflected* back into the same medium, and when it passes out of one medium into another, it is bent out of its former course, or *refracted*. The laws of reflexion and refraction constitute, severally, important departments of the science of Optics, and to these our attention will now be directed.

CHAPTER II.

OF THE REFLEXION OF LIGHT.†

855. *Light is said to be reflected when, on impinging upon any surface, it is turned back into the same medium.*

Instruments employed as reflectors are divided into *mirrors* and *speculums*. The name mirror is applied to reflectors made of glass and coated with quicksilver, as common looking glasses: the word speculum is applied to a metallic reflector, such as those made of silver, steel, tin, or a peculiar alloy called speculum metal. As the light which falls on glass mirrors, is intercepted by the glass before it is reflected from the quicksilvered surface, a speculum, or a reflector of polished metal, is that supposed to be employed in optical experiments, unless the contrary is specified. Such a surface, indeed, is to be understood where the word mirror is used without distinction.

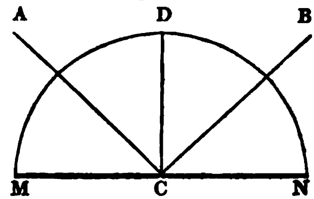
* Barlow.

† That part of Optics which treats of reflected light is sometimes denominated *Catoptrics* (Κατα), and that part which treats of refracted light, *Dioptrics* (Δια).

The surface of the mirror or speculum may be either plane, concave or convex, and the reflector is denominated accordingly.

A ray of light before reflexion is called the *incident* ray. The angle made by an incident ray, at the surface of the reflector, with a perpendicular to that surface, is called the *angle of incidence:* the angle made by the reflected ray with the same perpendicular is called the *angle of reflexion.* Thus, in Fig. 250, if MN represents the reflecting surface, DC a perpendicular to it at the point C, AC the incident, and BC the reflected ray; then ACD will be the angle of incidence, and BCD the angle of reflexion.

Fig. 250.



856. Experiments on light are usually conducted in a room which can be made dark with close shutters, one of which is perforated with a circular hole, a few inches in diameter, for admitting a beam of light. This opening is rendered smaller to any required degree by covering it with a piece of board or metallic sheet, having a smaller aperture. And, as the sun may not shine directly into the shutter at the time required, a mirror is sometimes attached to the outside of the shutter, so contrived that, by means of adjusting screws, it may be made to turn the rays of the sun into the opening, and to give them a horizontal or any other required direction. The course of the rays is rendered palpable to the eye, by the illuminated particles of dust that are floating in the air.

857. *The angles of incidence and reflexion are in the same plane, and are equal to each other.*

Let a ray of light AC (Fig. 250,) admitted into a dark chamber as above, be incident upon a horizontal speculum MN at the point C, to which the line CD is perpendicular, and let CB be the reflected ray. Then if the plane surface of a board or a metallic plate, be made to coincide with the incident ray and the perpendicular, it will be found to coincide also with the reflected ray, showing that the three rays are in the same plane. Again, if, from the point C, with the radius CA a circle be described, on measuring the arcs subten-

ded by the angles of incidence and reflection, they will be found to be exactly equal to each other.* The following corollaries will be evident on consideration:

That the complements of the angles of incidence and reflection, are also equal;

That the reflected ray may be taken for the incident ray, and vice versa;

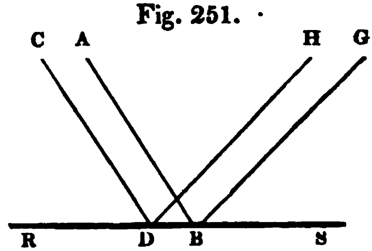
That, if the incident ray be perpendicular to the reflecting surface, it will be reflected back in the same line.

The angles of incidence and reflexion are also equal when the reflexion takes place from a concave or convex surface; for the reflexion being from a *point*, the curve and tangent plane at that point coincide, and have both the same perpendicular, namely the radius of the curve.

Reflexion of Light from Plane Mirrors.

858. *When rays of light are reflected from a plane surface, the reflected rays have the same inclination to one another as their corresponding incident rays.*

Fig. 251.

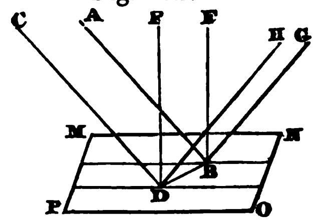


Case 1. *Parallel Rays.*—Let RS be the reflecting surface; AB, CD the incident, BG, DH the reflected rays. Then the angle ABR=GBS, and CDR=HDS; but since AB and CD are parallel, ABR=CDR; therefore, GBS=HDS, and BG, DH are parallel. In the foregoing example, the angles of incidence are supposed to be in the same plane; but where these angles are in different

* An ingenious apparatus is described by Biot (*Précis, Elem.* tome II, 136.) by which this experiment may be performed with the utmost degree of precision: the results are as enunciated in the proposition.

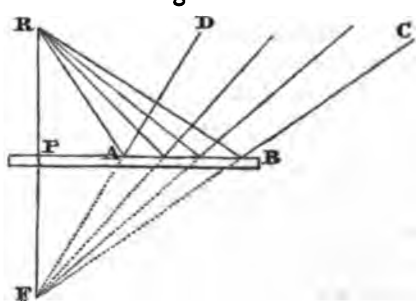
planes let AB, CD, (Fig. 252.) be two parallel rays incident upon the plane mirror MNOP; having their angles of incidence in different planes; from their points of incidence BD, draw the perpendiculars BE, DF; join BD, and let DH be the intersection of the two planes, CDH and GDBH. Since BE, DF are both drawn perpendicular to the same plane, they are parallel;* and as AB and CD are parallel by supposition, the angles of incidence ABE, CDF, are equal.† Because EB, FD, and AB, CD, are parallel, the planes ABG, CDH are also parallel,‡ and they are intersected by the plane GBDH; consequently DH is parallel to BG, and EBG=FDH. But EBG=angle of reflexion of AB; consequently, FDH=angle of reflexion of CD; and as DH is in the plane CDF, CD is reflected in the direction DH, which is parallel to BG.

Fig. 252.



Case 2. *Diverging Rays.*—Let RAB (Fig. 253.) be a pencil of diverging rays, incident upon the plane mirror PB, and from R draw RF perpendicular to PAB, and cutting the mirror in P. Let AD be the reflexion of an incident ray RA, and produce DA backward to F. Then PAR=BAD=PAF; consequently, in the right angled triangles PAR, PAF, the angles are all equal, and PA common; hence RP=PF, that is, the reflected ray proceeds as if it came from a point F, on the other side of the mirror, and from the same distance from it as P. In like manner it may be shown, that all the other rays will proceed as if they diverged from F, and therefore F is the virtual focus of all the reflected rays. Since PRA=PFA, it may be shown in the same way that PRB=PFB; hence, taking

Fig. 253.



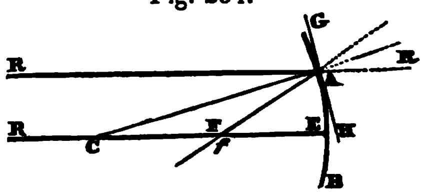
* Euc. 6, 2. Sup. † Euc. 9, 2. Sup. ‡ Euc. 13, 2. Sup.

equals from equals, the remainder AFB=ARB, that is, the rays after reflexion have the same inclination as before.

Case 3. *Converging Rays.*—If DA, CB, (Fig. 253.) constitute a pencil of incident rays converging to the point F, it follows from the above reasoning that they will converge to the focus R after reflexion.

859. *Parallel rays, incident upon a concave or convex mirror, are reflected to a focus equidistant from the surface and the center of the mirror.*

Fig. 254.



Let RA, RE, (Fig. 254.) be parallel rays incident upon the spherical mirror AEB, whose center is C. The ray RE, passing through the center C, and therefore falling perpendicularly on the mirror at E, will be reflected in the direction EC. Having joined CA, and made the angle CAF=CAR, the ray RA will be reflected in the direction AF. At the point of incidence A, draw the tangent GH, cutting CE produced in H. Then because RA and RE are parallel, the angle RAC=ACE=CAF; consequently CF=FA. But since CAH and CAG are equal, and likewise CAF and CAR, ∴ FAH=RAG=FHA ∴ FA=FH. If we now suppose the ray RA to approach the axis RE, the arc AE will diminish, and its secant CH will ultimately become equal to the radius CE, and then FH will be equal to FE, and of course FA or FC will equal FE.

The foregoing proposition is applicable to such rays only as are exceedingly near to the axis of the mirror CE. As the parallel rays are more remote from the axis, the focus F approaches nearer and nearer to the point E, until, when the arc EA becomes equal to 60°, F coincides with E; for then the angle CAF and ACF being each equal to 60°, the remaining angle of the triangle ACF must also be equal to 60°; consequently, CF must equal CA, and of course the point F will coincide with E.

860. If several beams of parallel rays be incident nearly perpendicularly upon a spherical mirror, the foci of the reflected rays, will be in a spherical surface concentric with that mirror. For since each focus (Fig. 254.) is by the proposition equidistant from the center of the mirror, the distances of all the foci from the mirror must be exactly the same; that is, they must be in a surface concentric with that of the mirror.

861. Rays falling on a concave mirror parallel to its axis, will all be brought to a focus at the same point, if the curvature of the mirror be that of a *parabola*. For then, according to a property of the parabola, all diameters, or lines parallel to the axis, and a line drawn from the focus to the point where the diameters meet the curve, make equal angles with the tangents at those points.* But these equal angles are the complements of the angle of incidence and reflexion which are also equal. Wherefore rays parallel to the axis will be reflected into the lines which all meet at one and the same focus.

862. DIVERGING RAYS *incident upon a concave mirror are collected into a focus, which changes its situation as the distance of the radiant from the mirror is changed, conformably to the law that the angle of incidence is equal to the angle of reflexion made with the radius of concavity.*†

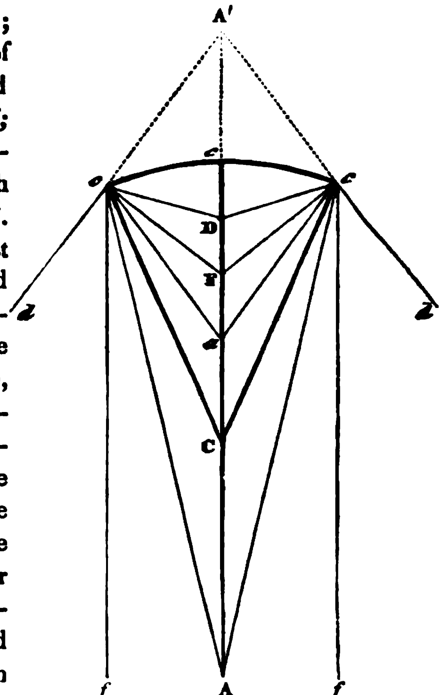
If the radiant point be farther from the mirror than the center, as at A, then the focus will be between the center and the mirror; if the radiant be at the center the rays will return to the center again; if the radiant comes still nearer to the mirror the focus will pass to the other side of the center and continue to recede from it, until the radiant has arrived at the place of the focus of parallel rays, when the focus on the other side of the center will be thrown to an infinite distance; and finally if the radiant be brought nearer to the mirror

* Conic. Sec.

† The several cases will be the more easily remembered, by keeping in mind the situation of the incident ray relative to the perpendicular, that is, the radius of concavity.

than the principal focus, the rays will go out diverging, and will never come to a focus; all which is evident from the general law of reflexion, the situation of each reflected ray being easily determined by that of the incident ray with respect to the perpendicular, that is, the radius of the mirror. Thus, the rays emitted from A will be collected in *a*; those from C will return to C again; those from *a* will be collected in A; those from F, the focus of parallel rays, will be reflected into the parallel lines *cf*, *cf*; and those from D into the diverging lines *cd*, *cd*, which will appear to proceed from A′. Again, if the radiant is first placed near the mirror, and removed from it by successive steps, just the converse effects will follow. Hence, the radiant and its corresponding focus are denominated *conjugate foci*. In the foregoing experiment, the conjugate foci approach one another—meet in the center of concavity—pass to different sides of that center, and afterwards recede from each other, until the focus nearest to the mirror arrives at the focus of parallel rays, when the two conjugate foci are separated to the greatest possible distance from each other.

Fig. 255.

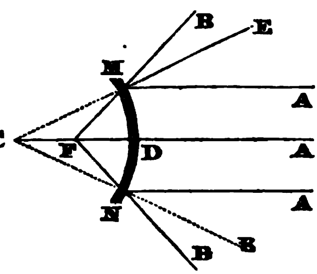


The point behind a concave mirror from which rays that diverge after reflexion appear to proceed, is called the *virtual focus*, as is represented by A′.

863. *Parallel rays incident upon a* CONVEX MIRROR *are made to diverge as from a point behind the mirror.*

Let MN (Fig. 256.) be a convex mirror whose center is C, and let AM, AD, AN be parallel rays falling upon it. Continue the lines CM and CN to E, and ME, NE will be perpendicular to the surface of the mirror at the points M and N. The rays AM, AN will therefore be reflected in the directions MB, NB, the angles of reflexion EMB, ENB, being equal to the angles of incidence EMA, ENA. By continuing the reflected rays BM, BN backwards, they will be found to meet at F, their virtual focus behind the mirror.

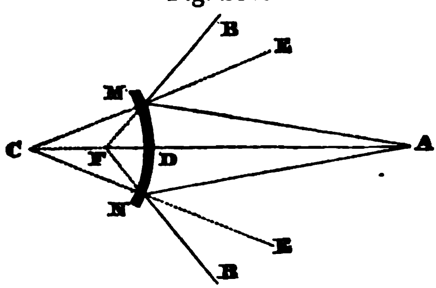
Fig. 256.



864. *Diverging rays incident upon a convex mirror are made to diverge as from a point behind the mirror, and nearer to it than the virtual focus of parallel rays.*

Let MN (Fig. 257.) be a convex mirror, C its center of convexity, and AM, AN rays diverging from A, which fall upon the mirror at the points M, N. The lines CME and CNE, will be, as before, perpendicular to the mirror at M and N; and, consequently, if we make the angles of reflexion EMB, ENB equal to the angles of incidence EMA, ENA, then MB, NB will be the reflected rays which, when continued backwards, will meet at F, their virtual focus behind the mirror. By comparing Figs. 256 and 257, it will be obvious that the ray AM in Fig. 257, is farther from ME than in Fig. 256, and consequently, the reflected ray MB must also be farther from it. Hence, as the same is true of the ray NB, the point F, where these rays meet, must be nearer D in Fig. 257, than in Fig. 256; that is, in the reflexion of diverging rays, the virtual focal distance DF is less than for parallel rays. For the same reason, if we suppose the radiant point A to approach the mirror, the virtual

Fig. 257.



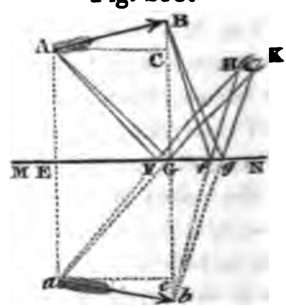
focus F will approach it; and when A arrives at D, F will also arrive at D. In like manner, if A recedes from the mirror, F will recede from it; and when A is infinitely distant, or when the rays become parallel, as in Fig. 256, F will reach the place of the virtual focus of parallel rays.

CHAPTER III.

OF IMAGES FORMED BY PLANE, CONCAVE AND CONVEX MIRRORS.

865. ***When any object is placed before a* PLANE *mirror, the image of it appears at the same distance behind it, of the same magnitude, and equally inclined to it.***

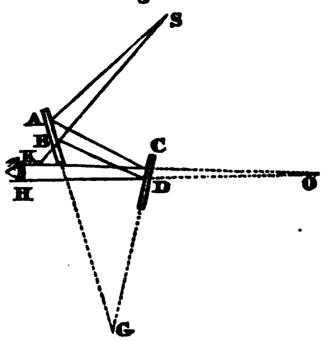
Fig. 258.



Let MN (Fig. 258.) be a plane mirror, and AB an object placed before it, and let the position of the object be such that the reflected rays may enter an eye placed at H. From A and B let fall upon the mirror the perpendiculars A*a*, B*b*. Then the rays AF, AG, diverging from A, will be reflected in the lines FH, GK, as if they came from the point *a*, so situated that EA=E*a*, (Art. 858.); and hence the point A, which is rendered visible to the eye at H by the rays FH, GK, will be seen at the point *a*. In like manner, it may be shown that the point B of the object, which is rendered visible to the eye at H by the rays *f*H, *g*K, will appear at *b*, so situated that GB=G*b*. By taking any other rays at pleasure, divergent from any other point of the object AB, it may, in a similar manner, be shown, that they will have their foci in points of the line *ab*, formed by drawing perpendiculars from the given points of the object. Now, since GB=G*b* and *a*G*b*=BGK =AGB, and G*a*=GA ∴ AB=*ab*. That is, the magnitude of the image equals that of the object. From A and *a* draw the perpendiculars AC, *a c*; then the angle BAC=*b a c*, that is, the object and the image are equally inclined to the mirror.

866. *If the image of an object is seen by reflexion from two plane mirrors, the reflexion being in a plane perpendicular to their common section, the angular deviation of the image from the object, will be equal to twice the inclination of the reflecting mirrors.*

Fig. 259.



Let AB, CD be two plane reflectors, inclined at the angle AGD; SB, BD, DH, the course of rays proceeding from some object, as a star, falling upon the mirrors, and finally converged to the eye at H. Then, because HBG = ABS = DBG ∴ the whole angle DBH=2DBG. In the same manner, BDO=2BDC. And since BGD = BDC − DBG ∴ 2BGD = 2BDC − 2DBG ∴ by substitution, 2BGD=BDO − DBH=BHD. But BHD is the angular deviation of the image from the object, and BGD is the inclination of the two mirrors. Hence, when a plane mirror revolves on an axis, the angular velocity of the reflected ray is double that of the mirror. Therefore, by turning a mirror through 45°, the image is carried through 90°, so that a mirror set at an angle of 45° with the horizon, represents horizontal objects in a perpendicular position, and perpendicular objects on a horizontal level.

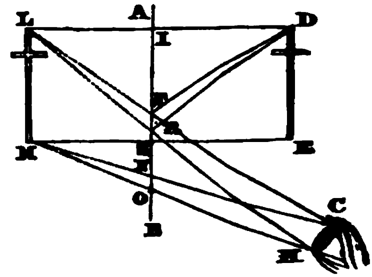
Upon the foregoing proposition depends the principle of Hadley's Quadrant, in which two mirrors, inclined to one another, measure the angular distance between two objects, by indicating the arc through which the image of one of them must be made to pass in order to carry that image over that distance.* Thus, if in order to make the image of a star descend to the horizon, the mirror that reflects it must be turned 20°, the altitude of the star is 40°.

867. *When the object is parallel to a plane mirror, the length or breadth of that part of the mirror upon which the image appears, is to the length or breadth of the object, as any reflected ray is to the sum of the incident and reflected rays.*

* See Day's Navigation and Surveying, Art. 91.

If the object DE is parallel to the mirror AB, and the image LM is seen by the eye at C, then FN, the length of that part of the mirror which is taken up by the image, subtends the angle LCM, under which the image appears. Now the length of the image LM is equal to the length of the object DE. (Art. 865.)

Fig. 260.



And because FN is parallel to LM $\therefore$ FN : LM :: CF : CL. But CF is the reflected ray and CL is equal to the sum of the incident and reflected rays.

Hence an object which is not wholly visible when the eye is at a certain distance from the mirror, may become so by bringing the eye nearer to the mirror; for in proportion as the ratio of the reflected ray to the sum of the incident and reflected rays is diminished in the same proportion is the part of the mirror required to comprehend the entire image diminished.

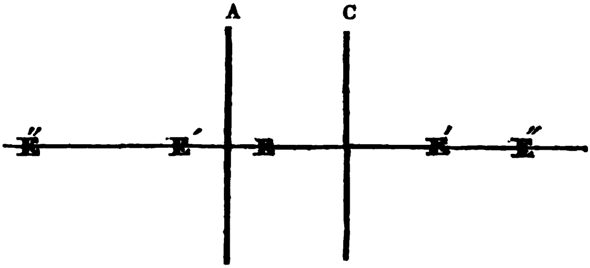
If a spectator sees himself entirely in a plane mirror placed parallel to him, the mirror must be half as long as himself. For then the incident and reflected rays will be equal, and consequently the latter equal to half the sum of the two, and hence the mirror must be *half* the length of the object.

868. *When an object is placed between two parallel plane reflectors, a row of images is formed in each mirror, appearing in a straight line behind each to an indefinite extent.*

Let there be two plane reflectors, parallel to each other; and let an object, a candle for example, be placed between them. An image of the candle will be formed in each mirror, as far behind it as the object is before it. Again each of these images becomes in its turn a new object to the opposite mirror, and forms a corresponding image as far behind that mirror as it is itself before it, and thus the images are repeated in a right line until the light becomes too feeble to

be visible. Thus let AB, CD, (Fig. 261.) be two plane mirrors, and E an object between them: two images will be formed of E at E′ and E′; two more of E′ and E′ at E″ E″; and thus a succession

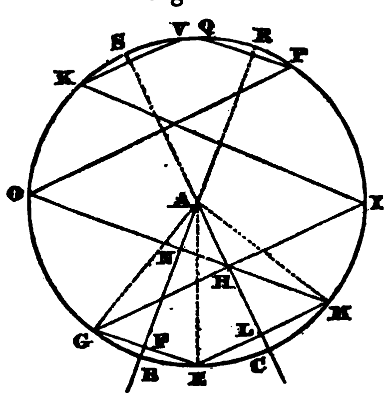
Fig. 261.



of images will arise to an indefinite extent; but since a certain part of the light is lost at every reflection; each succeeding image is fainter than the preceding. The *Endless Gallery* is formed on this principle. It consists of a box in the opposite sides of which are placed two parallel reflectors, and between them a number of images are placed, which are repeated in an endless succession.

869. *If an object be placed between two plane reflectors inclined to each other, the images formed will lie in the circumference of a circle whose center is in the intersection of the two planes, and whose radius is the distance of the object from that point.*

Fig. 262.



Let AB, AC, (Fig. 262.) be two plane reflectors inclined at the angle BAC, and E an object placed between them. Draw EF perpendicular to AB, and produce it to G, making FG=EF; then the rays which diverge from E and fall upon AB will, after reflexion, diverge from G; or G will be an image of E. From G, draw GH perpendicular to AC, and produce it to I, ma-

king HI=GH, and I will be a second image of E, &c. Again draw ELM perpendicular to AC, and make LM=EL; also draw MNO perpendicular to AB, and make NO=MN, &c. Therefore, the successive images formed, beginning on the side of AB, are G, I, K, V; and those on the side of AC, are M, O, P, Q. Then, since EF is equal to FG, and AF common to the triangles AFG, AFE, and the angles at F are right angles, AG is equal to AE. In the same manner it may be shown, that AM, AO, AI, &c., are severally equal to AE; and of course, the points G, M, O, I, &c., are in the circumference of a circle whose center is A and radius AE.

If the angle BAC is finite, *the number of images will be limited.* For BA and CA being produced to S and R, the rays which are reflected from either surface, diverging from any point Q and between S and R, will not meet the other reflector, since it is not before either reflector, but behind both.

If we consider the whole angular opening of the mirrors, namely, the *sector* ABC *as the object*, images of it will be formed in a circle as of any other object.

If the inclination of the mirrors gradually diminishes, the magnitude of the sectors will also be diminished and the number of repetitions of them increased in the same proportion. The number of images of any object placed between the mirrors will be in like manner increased as the inclination of the mirrors is diminished; and since, when the angle of inclination is very small, the mirrors approach the situation of parallel mirrors, so the number of images approach to infinity.*

870. The degree of perfection in the polish and figure of a plane speculum, may easily be known by observing whether the images seen in all positions, especially in very oblique ones, and from all parts of the speculum, appear exactly equal and similar to the objects; that is, whether the images (more particularly of the most distant objects) in the room, appear naturally, without having any part of them distorted; when this is the case, the speculum may be pronounced to be a perfect one. The straight edges of the rails of wainscot are the best objects for this experiment. A mirror must

* See Art. 868.

be exceedingly bad, that will distort the face of a person looking into it, because the rays being returned almost directly back to the eye, small aberrations will not be rendered sensible; but let two persons look at each other's image as obliquely as they can, and they will soon perceive whether or not the figure of the speculum is defective. In all speculums, the better they are polished, other circumstances being the same, the brighter will be the images; that is the more light an eye will receive from a given object, which will enable us to examine the goodness of speculums, as to their polish, whenever we have an opportunity of comparing several of the same sort, and in the same light together. We may also observe that, *cæteris paribus*, the darker the color of the speculum is, the better is the polish; for the glass itself can be no otherwise seen, than by the reflexions of those particles which have irregular positions with respect to the rest of the surface. But different glasses though equally well polished, will not always appear equally dark; generally, however, the above rule may be observed.*

871. It is found by experiment, that when a pencil of light is incident perpendicularly upon *water*, only 18 rays out of 1000 are reflected while the greater part of the remaining rays are transmitted. As the angle of the inclination is increased, the proportion of rays reflected is also rapidly increased, till at angle of 75° the reflexion is 211 rays; at 85°, 501; and at 89°, 692. In *glass* 25 out of 1000 are reflected at a perpendicular incidence; and the glass always reflects more light than water, till we reach very great angles of incidence such as 87½°, when it reflects only 584 rays, while water reflects 614.

872. *When an object is placed before a concave mirror, the image of it has various magnitudes and positions depending on the distance of the object from the mirror.*†

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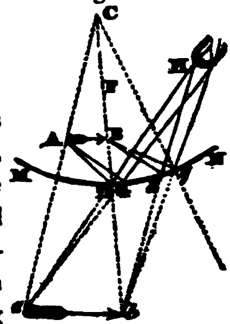
* Barlow.

† These different places of the image depend on the principles demonstrated in Art. 862, and they will be easily remembered by considering the relation of the incident rays to the perpendicular, that is the radius of concavity, conformably to the general laws of reflexion. (Art. 857.)

1. When an object is *between the mirror and the focus of parallel rays*, the image appears behind the mirror, and is more distant from it and larger than the object. Let MN, Fig. 263, be the concave mirror, F its principal focus, C its center, and AB the image. From C draw CA*a*, CB*b*, passing through A and B, and let the image be so placed that the reflected rays will reach the eye at H. The rays AD, AG, proceeding from A, and B*d*, B*g*, proceeding from B, will be reflected to the eye at H, making equal angles with the perpendiculars CG, C*g*, &c. and they will diverge less than before reflexion, as if they had come from a remote point *a*, situated in the intersection of those rays with the perpendicular CA*a*. In like manner the rays B*d*, B*g* will enter the eye at H, as if they had proceeded from *b*, a point where they intersect CB*b*. These points *a*, *b*, will be farther from MN then A and B are, and the image *ab* will be greater than AB, in the ratio of C*b* to CB.

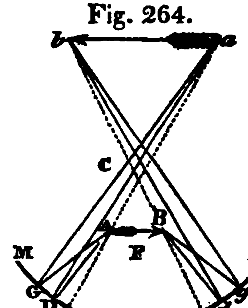
Fig. 263.



2. When the object is placed *in the principal focus*, the rays will go out parallel and will never come together so as to form an image of themselves, nor will they proceed from any point behind the mirror, so as to form an imaginary image, like that of case 1.

3. When the object is situated *between the principal focus and the center*, the image is formed on the other side of the center, and is inverted and larger than the object.—Let MN (Fig. 264.) be the mirror, C its center, F its focus and AB the object, through C draw the lines CA, CB, and continue them backwards to *a* and *b*. Then let AD, AG and B*d*, B*g*, be two sets of rays flowing from the extremites A. B. These rays will, after reflexion in the directions D*a*, G*a*, and *d b*, *g b*, meet the perpendicular lines C*a*, C*b*, in the points *a b*, at a greater distance from the mirror than the center C, and will there form an image of those points of the object. The image is therefore more remote from C than the object is, and the size of the one

Fig. 264.



will be that of the other as aC is to AC; that is, the image will be larger than the object.

4. When the object is situated *beyond the center*, the image will then be formed between the centre and the principal focus, and will be inverted and less than the object. This is the converse of the preceding, and will be made obvious by considering the rays as first flowing from a b and converged to AB.

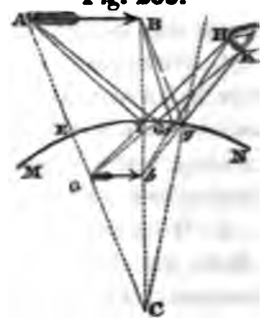
5. When the middle part of the object is placed *in the center* of the mirror, the object will coincide with the image, and the image will be inverted. That the center of the image will coincide with that of the object may be inferred from (Art. 862.) the reflected ray being returned back in the incident ray or perpendicular; and the extremities of the object A and B will make equal angles with this perpendicular on the different sides of it, and therefore an inverted image will fall back upon the object.

873. The following experiments, which may be easily repeated, will serve to render familiar the different cases above demonstrated.

We will suppose a lighted candle to be placed very near to a concave mirror:—it will form no image before it because the rays go out still diverging, but we see an enlarged image of the candle behind the mirror. As the radiant is withdrawn from the mirror towards the principal focus, the image will rapidly recede on the other side, and grow larger and larger until the radiant reaches the focus, when the image will suddenly disappear. On removing the radiant a little farther, the image will be found at a great distance before the mirror and very much enlarged. As the radiant approaches the center, the image approaches it rapidly on the other side of it, constantly diminishes in size until they both meet and coincide in the center. Removing the radiant still farther, the image appears again between the center and the focus, diminished in size, and slowly approaching the focus as the radiant recedes but never reaches it, unless when the radiant may be considered as at an infinite distance, as in the case of the heavenly bodies. By applying principles already explained, the learner will readily account for these various appearances.

874. *When any object is placed before a* CONVEX *mirror, the image of it appears nearer to the surface of the mirror, and of a less size.*

Fig. 265.



Let MN be a convex mirror whose center is C, and AB the object, and let the position of the object be such, that a reflected ray may enter the eye placed at H. From C, draw CA, CB, cutting the mirror MN in E and F. The rays AF, AG, will be reflected to H and K, making equal angles with the perpendicular passing from C through F and G, and will therefore enter the eye as if they came from some point as *a*, at the intersection of these rays with the perpendicular AC; consequently the point A of the object will have its image visible at *a*. In like manner rays B*f*, B*g*, falling upon the points *f*, *g*, will be reflected to the eye as if they came from *b*, the point where they intersect the perpendicular drawn from B to C. Now as the reflected rays diverge more than the incident ones, the point *a* will be nearer the mirror than A, and the image *ab* will be less than the object AB, in the ratio of C*b*, to CB.

875. *In spherical mirrors, concave or convex, the diameter of the object is to the diameter of the image, as the distance of the object from the center is to the distance of the image from the center; and also as the distance of the object from the surface is to the distance of the image from the surface.*

It is evident from Figs. 264, 265, that the object and the image subtend each the same angle, both at the center, and at the surface; and as they are parallel to one another their lengths are as their distances from these points respectively.*

876. One who looks into a concave mirror sees his own face varied in the following manner.

When he holds the reflector near to his face, he sees his image *distinct*, because the rays come to the eye diverging (which is their natural state with respect to near objects,) and *enlarged*, because, as

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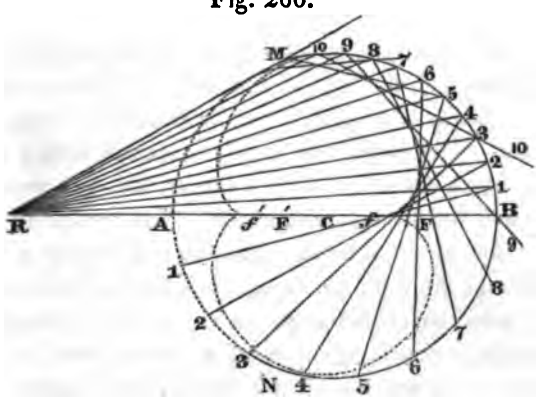
* Euc. VI. 4.

the rays diverge less than before, the image is thrown back to a greater distance behind the mirror than the object is before it, and the magnitude is as that distance by article 875. As he withdraws the eye, the image grows larger and larger until the eye reaches the focus. From the focus to the center, no distinct image is seen, because the rays come to the eye converging, a condition incompatible with distinct vision. At the center the eye sees only its own image, since the image is reflected back to the object and coincides with it. Beyond the center, his face will be seen on the other side of the center before the mirror (though habit may lead him to refer it to a point behind it); and it will be *diminished*, being nearer to the mirror than the object is (Art. 875.) and *inverted*, because an inverted image is formed when the rays are brought to a focus, and this becomes the object which is seen by the eye.*

877. *By the reflexion of light from concave mirrors, there are exhibited a peculiar kind of curves called* CAUSTICS BY REFLEXION.†

Fig. 266.



Let MBA be a concave spherical mirror whose center is C, and whose focus for parallel and central rays is F. Let RMB be a di-

* These phenomena may be all observed with an ordinary concave shaving glass.

† Called caustics or *burning* points, because since the rays of light or heat cross each other in the points that make up these curves, the intensity of light or heat is twice as great there as elsewhere.

verging beam of light falling on the upper half, MB, of the mirror at the points 1, 2, 3, 4, &c. If we draw radii to all these points from the center C, and make the angles of reflexion equal to the angles of incidence, we shall obtain the directions and foci of all the incident rays. The ray RI, near the axis RB, will have its conjugate focus at f, between F and the center C. The next ray, R2, will cut the axis nearer F, and so on with all the rest, the foci advancing from F to C. By drawing all the reflected rays to these foci, they will be found to intersect one another as in the figure, and to form by the intersections the *caustic curves* Mf. They are so called because, in consequence of the intersections of the rays in the points forming these curves, those points are brighter, or, where heat is reflected, hotter, than the contiguous spaces. If the light had also been incident on the lower half of the mirror, a similar caustic, shown by a dotted line, would also have been formed between N and f. If we suppose, therefore, the point of incidence to move from M to B, the conjugate focus of any two contiguous rays or an infinitely slender pencil diverging from R, will move along the caustic from M to f.

878. Concave mirrors, in consequence of the property they have of forming images in the air, were in a less enlightened age than the present, frequently employed by showmen for exhibiting surprising appearances. The mirror was usually concealed behind a wall, and the object, which might be a skull, a dagger, &c. was placed between it and the wall and strongly illuminated. The rays proceeding from the object fell upon the mirror and were reflected by it through an opening through the wall, and brought to a focus so as to form an image in the same room with the spectator. If a fine transparent cloud of blue smoke is raised, by means of a chafing dish, around the focus of a large concave mirror, the image of any highly illuminated object will be depicted in the middle of it with great beauty. A dish of fruit thus represented invites the spectator to taste, but the instant he reaches out his hand a drawn dagger presents itself.

879. Concave mirrors have been used as *light house reflectors*, and as *burning instruments*. When used in light houses, they are formed of copper plated with silver, and they are hammered into a parabolic form, and then polished with the hand. A lamp placed

in the focus of the parabola, will have its divergent light thrown, after reflexion, into something like a parallel beam, which will retain its intensity to a great distance.

When concave mirrors are used for burning, they are generally made spherical, and regularly ground and polished upon a tool, like the specula used in telescopes. The most celebrated of these were made by M. Villele, of Lyons, who executed five large ones. One of the best of them, which consisted of copper and tin, was very nearly four feet in diameter, and its focal length thirty eight inches. It melted the metals, as silver and copper, and even some of the more infusible earths.

Burning mirrors, however, have some times been constructed on a much larger scale by combining a great number of plane mirrors. It is supposed that it was a mirror of this kind which Archimedes employed in setting fire to the Roman fleet under Marcellus. Athanasius Kircher, who first proved the efficacy of a union of plane mirrors, went with his pupil Scheiner to Syracuse, to examine the position of the hostile fleet; and they were both satisfied that the ships of Marcellus could not have been more than *thirty* paces distant from Archimedes.

Buffon, the celebrated naturalist, constructed a burning apparatus upon this principle, which may be easily explained. He combined one hundred and sixty eight pieces of mirror six inches by eight, so that he could, by a little mechanism connected with each, cause them to reflect the light of the sun upon one spot. Those pieces of glass were selected which gave the smallest image of the sun at two hundred and fifty feet. With one hundred and fifty four mirrors, he was able to fire combustibles at the distance of two hundred and fifty feet.

CHAPTER IV.

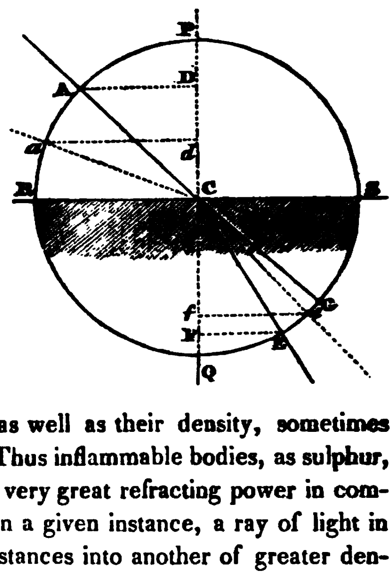
OF THE REFRACTION OF LIGHT.

880. When the rays of light pass out of one medium into another, as out of air into water, they are bent out of their previous direction; and hence,

Refraction is the change of direction which light undergoes by passing out of one medium into another.

The lines which a ray describes before and after refraction are called *incident* and *refracted* rays; the angle contained between the incident ray and a perpendicular to the surface drawn from the point on which the ray falls, is called the *angle of incidence:* the angle contained between the refracted ray, and the said perpendicular, is called the *angle of refraction*. The angle which the refracted ray makes with its previous line of direction is called the *angle of deviation*. These several definitions the learner will easily apply to the following figure. Thus AC is the incident, and CE the refracted ray; ACD is the angle of incidence, ECF the angle of refraction, GCE the angle of deviation. It is a general fact, to which there are only a few exceptions, that a ray of light in passing out of a rarer into a denser medium is refracted *towards* a perpendicular to the surface; and in passing out of a denser into a rarer medium refracted *from* the perpendicular. But the chemical constitution of bodies as well as their density, sometimes affects their refracting power. Thus inflammable bodies, as sulphur, amber, and essential oils, have a very great refracting power in comparison with other bodies; and in a given instance, a ray of light in passing out of one of these substances into another of greater density but of less refractive power, might not be turned towards, but from, the perpendicular.

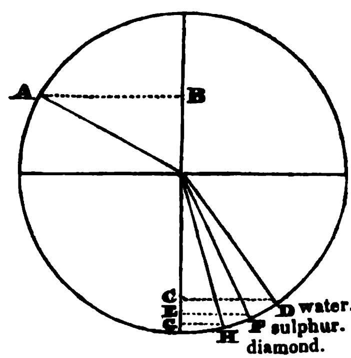
Fig. 267.



881. *When a ray of light passes from one medium into another of different density, the sine of the angle of incidence and refraction have always the same ratio to each other; and the incident and refracted rays are in the same plane.*

This proposition is proved by experiment. Let AC (Fig. 267.) be a ray of light incident upon the surface RS of water, or any other medium. This ray, instead of proceeding directly forward in AC produced, is bent or refracted at C into the direction CE. In like manner, another ray *a*C, incident upon the same point C, is found to be bent or refracted into the line C*e*. Through the point C draw the line PCQ perpendicular to the refracting surface RS, and upon C as a center, describe a circle ABE*a*. If we now compare the *angles* of refraction with the corresponding angles of incidence, we shall perceive no particular relation between them, except that, in general, one increases or diminishes with the other; but if we compare the *sines* of these angles, viz, AD with EP, and *a d* with *e f*, we shall find that the ratio of the one to the other is constant, whatever be the value of the angles of incidence or refraction. If the surface RS is that of *water*, into which a ray passes from the atmosphere, the ratio of the sines of incidence and refraction will be as 4 to 3 nearly, and this ratio will always be the same at whatever angles the ray enters the medium. From air into *crown* glass, the ratio is as 3 to 2; from air into *sulphur*, as 2 to 1; from air into *diamond*, as 1 to $\frac{2}{5}$. (See Fig. 268.)

Fig. 268.



By admitting the light through a small aperture at A, (Fig. 267.) so as to pass through another aperture at C, and fall upon the bottom of the vessel at E, it will be found by experiment that the three points A, C, E, are always in the same plane, whatever be the angle of incidence ACP; that is, the incident and refracted rays are always in the same plane.

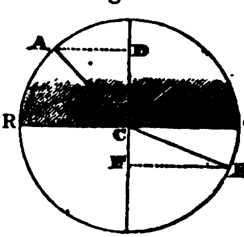
882. Supposing the sine of the angle of refraction to be always 1, then the sine of the angle of incidence will be nearly 1.33 in water, and 1.5 in glass. The sine of the angle of incidence, that of refraction being taken for unity, is called the INDEX OF REFRACTION. Thus

the index of refraction for sulphur is 2; for the diamond 2.5, &c. Rays of light which pass perpendicularly out of one medium into another, suffer no refraction; for since the sine of the angle of incidence then becomes nothing, that of refraction likewise becomes nothing, and of course the angle of refraction is nothing. When the ray passes in the opposite direction, that is, from a denser into a rarer medium, as from water into air, the same constant ratio is found to exist between the sines of incidence and refraction. Thus (Fig. 267.) the light from E to C will pass into CA, and the ratio of the sines of incidence and refraction will be that of EF to AD. In this case the index of refraction is less than unity.

We see an example of the foregoing principle in the bent appearance of an oar in the water, the light of the part immersed (by which it is visible) being turned from the perpendicular, and causing it to appear higher than its true place. In the same manner, the bottom of a river appears elevated, and diminishes the apparent depth of the stream. The following ancient experiment illustrates the same principle. If a small piece of silver be placed in the bottom of a bowl, and the eye be withdrawn until the piece of silver disappears, on filling up the bowl with water, the silver comes into view again.

883. *A ray of light cannot pass out of a denser into a rarer medium, when the angle of incidence is greater than that at which the sine of the angle of refraction becomes equal to radius.*

Fig. 269.



Let AC (Fig. 269.) be the ray incident upon the rarer medium RS. It will be refracted from the perpendicular DF into the direction CE, so that AD is to EF in a constant ratio. (Art. 881.) If we increase the angle ACD, the angle FCE will also increase till the lines CE and FE coincide with the radius CS. But if beyond this position of the ray AC, the angle ACD is still farther increased, it is manifest that its sine is also increased; and, consequently, in order that the ratio may be constant, the sine of refraction EF must also increase, which is impossible, since it is already by hypothesis equal to the radius CS. Hence it follows, that when-

ever the angle of incidence is greater than that at which the sine of the angle of refraction becomes equal to radius, the ray cannot be refracted consistently with the constant ratio of the sines.

This is found to be the case by experiment; and at the angle thus indicated, all the incident rays are *reflected* from the inner surface of the denser medium, having a reflexion more brilliant than what can be produced from any metallic surface. This reflexion is then called *total reflexion*.

The angle at which total reflexion takes place may be found thus: Let x be the sine of incidence at which the corresponding sine of refraction is 1, or equal to radius, and let m represent the index of refraction or the ratio of the sines, (Art. 882.) then $x : 1 :: 1 : m$, $\therefore x=\frac{1}{m}$; that is, total reflexion takes place when the sine of incidence is equal to the reciprocal of the index of refraction.

In *water*, whose index of refraction is 1.336, the angle of total reflexion is 48° 28′. In *glass*, whose index of refraction is 1.50, it is 41° 49′. In *sulphur* it is 30°; and in *diamond* it is 23° 35′.

884. *Transparent bodies differ much among themselves in refracting power.*

The following table will be useful by way of reference.

Table of Refractive Powers.

	Index of Refraction.
Chromate of Lead,	2.974
Red Silver Ore,	2.564
Diamond,	2.439
Phosphorus,	2.224
Sulphur, (melted)	2.148
Glass, (composed of lead two parts, flint one,)	1.830
Sapphire and other precious gems,	1.800
Sulphuret of Carbon,	1.768
Oil of Cassia,	1.641
Quartz, or rock crystal,	1.548
Amber,	1.547
Crown Glass,	1.530
Oil of Olives,	1.470
Alum,	1.457

Fluor spar,	1.434
Mineral Acids,	1.410
Alcohol,	1.372
Water,	1.336
Ice,	1.309
Tabasheer,	1.111

Hence it appears that certain salts of silver and lead, the diamond, phosphorus, and sulphur, rank highest in refracting power; next come the precious gems, and flint glass containing a large proportion of the oxide of lead, which has a refracting power considerably higher than crown glass containing less metallic oxide; to which succeed the aromatic oils. Among transparent solids, fluor spar is distinguished for its low refracting powers; but tabasheer, a substance formed from the concreted juice of the Indian bamboo, is more particularly remarkable for the same property. Figure 268 will convey an idea of the refractive properties of several of these substances.

In the preceding table the refractive powers of different bodies are given without any consideration of their densities or specific gravities; but it is evident, that if a body of small specific gravity has the same refractive power as another body of greater specific gravity, the former must have a greater *absolute* action upon light than the latter. Hence, in order to measure the absolute refractive powers of bodies, their specific gravities must be taken into the account. When estimated on this principle, *hydrogen* will be found to have the greatest refractive power of all bodies, it being, according to Dr. Brewster, equal to 3.0953; and it is also the most inflammable of all bodies. It was in consequence of the high refractive properties of inflammables, that Sir Isaac Newton expressed the opinion that the diamond is a body of this class, before its chemical constitution had been discovered.*

885. The *Prism* is an important instrument in Optics, especially as it affords the means of decomposing light, and enters into the construction of several optical instruments. The *triangular* prism is the only one employed in experiments, and of this nothing more is essential than barely the inclination of two plane transparent surfaces to one another. The optical prism, however, is usually understood

* It is now known to consist of carbon, or pure charcoal.

to be a piece of solid glass, having two sides constituted of equal parallelograms, and a third side called the *base*. The line of intersection of the two sides is called the *edge*, and the angle contained by the sides, the *refracting angle* of the prism. A straight line passing lengthwise of the prism, through its center of gravity and parallel to the edge, is called the *axis*. A section made by a plane perpendicular to the axis, is an isosceles triangle. Frequently, the three angles of the prism are made equal to one another, each being 60°.*

Fig. 270.

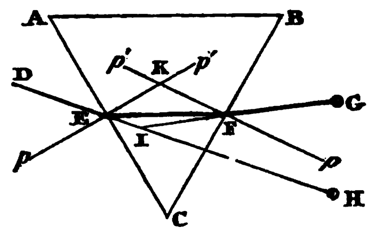


Figure 270 represents a section of a prism ABC, of which AB, is the *base*, and ACB the *refracting angle*. DE is a beam of the sun's light falling obliquely on the first surface AC where one portion is reflected but another portion transmitted. The latter portion instead of passing directly forward and forming an image of the sun at H, is turned upward towards the perpendicular *pp'*, meeting the opposite surface CB in F, where it is again turned upward from the perpendicular *p'p* in the direction FG, carrying the image of the sun from H to G. If the incident and emergent rays be produced so as to meet in I, the angle FIH is called the *angle of deviation*.

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* A very convenient prism for common experiments may be constructed as follows. Select two plates of window glass of the best quality, or better, two pieces of looking glass, from which the silvering has been removed. The plates may be five or six inches long, and one and a half or two inches broad. They are to be united at their edges at an angle of about 60°, and furnished with a tin case, which shall afford the base and the two ends, and a covering for the edge. One of the ends has an orifice with a stopper, for the convenience of filling with a fluid, which may be pure water, or better a saturated solution of the sugar of lead filtered perfectly clear. Projections may be attached to the two ends to serve as handles or as an axis on which the prism may rest on supports. Instead of the tin case, we may employ a block of hard wood, first formed into a triangular prism, and then dug out so as to admit the plates.

886. By means of the prism the index of refraction for different bodies may be found very conveniently from the following theorem.

The index of refraction diminished by unity, is always equal to the angle of deviation divided by the refracting angle of the prism.

In demonstrating this proposition it is necessary to premise, that when angles are small their ratio is nearly that of their sines; and since the sine of the angle of incidence is to that of refraction as the index of refraction to unity (Art. 882.) therefore, n being the index of refraction, (see Fig. 270.)

$$p'\mathrm{EI}(=\mathrm{DE}p) : p'\mathrm{EF} :: n : 1 \therefore$$
$$\mathrm{FEI} : p'\mathrm{EF} :: n-1 : 1$$
$$\text{also, } p'\mathrm{FI}(=\mathrm{GF}p) : p'\mathrm{FE} :: n : 1 \therefore$$
$$\mathrm{EFI} : p'\mathrm{FE} :: n-1 : 1 \therefore$$
$$\mathrm{FEI}+\mathrm{EFI} : p'\mathrm{EF}+p'\mathrm{FE} :: n-1 : 1 \therefore$$
$$\mathrm{FIH} : p'\mathrm{KF} :: n-1 : 1$$

But p'KF and ACB are equal, being each a supplement to four right angles in the quadrilateral figure ECFK. Therefore, FIH : ACB $::n-1 : 1 \therefore$

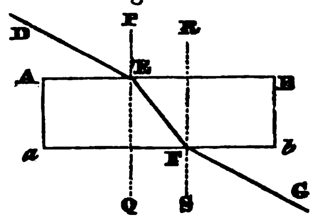
$$\overline{n-1} \times \mathrm{ACB} = \mathrm{FIH}$$
$$n-1 = \frac{\mathrm{FIH}}{\mathrm{ACB}} \qquad \text{Q. E. D.}$$

Now in prisms of glass $n=\frac{3}{2}$; therefore, $\frac{\mathrm{FIH}}{\mathrm{ACB}}=\frac{1}{2}$ or $\mathrm{FIH}=\frac{1}{2}\mathrm{ACB}$; that is, the angle of deviation equals half the refracting angle of the prism.

In order to find the index of refraction for any solid substance, the substance itself may be formed into a prism. The refracting angle of the prism being always known, and the angle of deviation easily measured, the index of refraction is readily found, by dividing the latter angle by the former, and adding one to the quotient. If the substance is of such a nature, that it cannot be fashioned into a prism, as a liquid, for example, it may then be introduced into the refracting angle of a prism formed by two plates of glass inclined to each other.

887. *When light is transmitted through a medium bounded by plane and parallel surfaces, the incident and emergent rays are parallel.*

Fig. 271.



Let AB*ba* be the medium bounded by parallel surfaces AB, *ab;* and let DE be the incident ray refracted in the direction EF, and emerging in the direction FG; the ray FG will be parallel to DE. Through the points E, F, draw the perpendiculars PQ, RS. Then, since PQ and RS are parallel, the angle of refraction QEF at the first surface, is equal to EFR, the angle of incidence at the second surface; but as the ratio of the sine of QEF to DEP is the same as that of EFR to SFG, (Art. 882.) the angles DEP and SFG must be equal, and consequently, their complements AED, *b*FG; and if we add to these the equal angles AEF, *b*FE, the whole angles DEF, GFE will be equal, and consequently the rays DE, FG parallel.*

It is found by experiment that when light is transmitted through *two* contiguous mediums, the incident and emergent rays are parallel to one another.†

888. *Through a plane surface, if diverging rays pass out of a rarer into a denser medium, they are made to diverge less than before: if out of a denser into a rarer medium, to diverge more.*

For since the sine of the angle of refraction is always as that of incidence, the most divergent lines in a pencil will be the most refracted, and will of course be brought nearer to a parallelism with those rays which diverge less when the refraction is *towards* the perpendicular, but will be still farther separated when the refraction is *from* the perpendicular.

889. *Lenses*, on account of their extensive use in the construction of optical instruments, require very particular attention in the study of Optics. They are of several varieties as is shown in the following figure.

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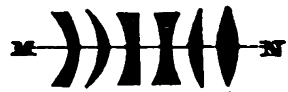
* Euc. I. 27. † Wood's Optics, p. 50.

Fig. 272.



A *double convex lens* (A) is a solid formed by two segments of a sphere applied base to base.*

A *plano-convex lens* (B) is a lens having one of its sides convex and the other plane, being simply a segment of a sphere.

A *double concave lens* (C) is a solid bounded by two concave sperical surfaces which may be either equally or unequally concave.

A *plano-concave lens* (D) is a lens one of whose surfaces is plane and the other concave.

A *meniscus* (E) is a lens, one of whose surfaces is convex and the other concave, but the concavity being less than the convexity, it takes the form of a crescent, and has the effect of a convex lens whose convexity is equal to the difference between the sphericities of the two sides.

A *concavo-convex lens* (F) is a lens one of whose surfaces is convex and the other concave, the concavity exceeding the convexity, and the lens being therefore equivalent to a concave lens whose sphericity is equal to the difference between the sphericities of the two sides.

A line (MN) passing through the center of a lens perpendicular to its opposite surfaces, is called the *axis*.

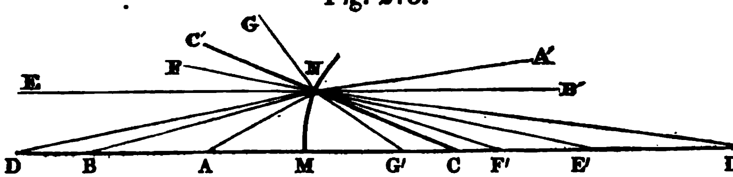
890. The manner in which light is refracted into denser or rarer mediums bounded by spherical surfaces, may be readily understood and easily remembered, by keeping in mind the position of the incident rays with respect to the perpendicular, that is the radius of the spherical surface. Suppose the two mediums are air and glass, and let us take first, the case of a *convex* surface of glass: then, since rays passing into the glass would be turned towards the perpendiculars (all of which being radii, tend towards a common center) parallel rays would be made to converge; diverging rays would become less diverging; converging rays, more converging. These are the *general* results; but let us trace the progress of diverging and converging

* Though this is the most common form of the double convex lens, yet it is not essential that the two segments should be portions of the same sphere: they may be segments of different spheres in which case the curvatures will be unequal on the two sides of the lens.

rays a little more particularly. If the rays came from a near radiant so as to diverge very much from each other, the effect of the glass would be simply to *diminish* their divergency; but if they came from some more distant point, so as to be less diverging, they might be turned so far towards the perpendicular as to become parallel, or even converging. But suppose the incident rays to come to the glass converging, then if they were directed towards the center of the sphere they would coincide with the radii or perpendiculars and suffer no change of direction; if they originally tended to a point more distant than the center, being turned towards the radii, they would be rendered more convergent; but if they tended towards a point nearer than the center, for the same reason they will converge less than before.

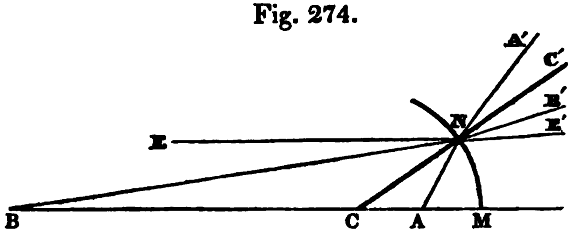
These several cases will be rendered familiar by studying the representation in Fig. 273.*

Fig. 273.



891. Secondly, let us consider the case of a *concave* surface. We shall perceive, by inspecting Fig. 274, that *parallel* rays, by

Fig. 274.



being turned towards the perpendicular, are made diverging; *diverging* rays are, in general, rendered more diverging, but when they come from the center of concavity, they suffer no refraction, and when from a point nearer the surface than the center, they diverge

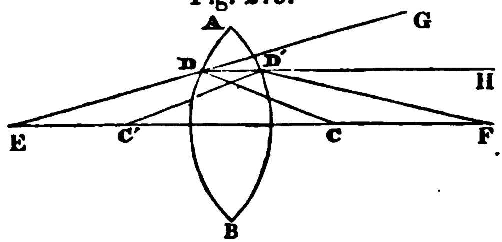
* The student is expected to make the explanation of each case from the figure, following the rays AN, &c. to GN.

less than before; and *converging* rays are, in general, rendered less converging, but they may be so slightly convergent before, that the refracting power of the glass shall be sufficient to render them parallel or even divergent.

892. Thirdly, if we now trace the progress of the rays through LENSES, we shall readily follow their course by applying the foregoing principles.

1. Let AB be a double *convex* lens, C C′ the centers of curvature, and ED a ray of light falling upon the lens at D. According

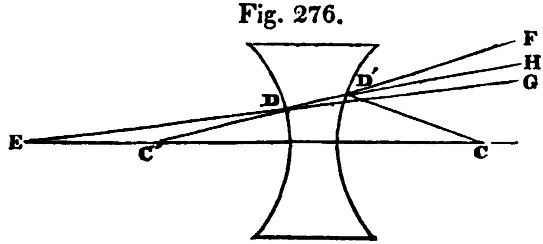
Fig. 275.



to the principles just explained, ED would be turned towards CD, the perpendicular to the refracting surface, and instead of passing onward in the same straight line EDG, it would proceed in the line D D′. Again, on passing out of the denser into the rarer medium at the second surface at D′, instead of proceeding onward in the line DD′H it would be turned farther from the perpendicular to that surface, namely C′D′, so as to proceed in the line D′F. Both surfaces of the lens, therefore, conspire to turn the ray out of its former course, and when the curvature of the two sides is the same, they contribute equally to produce this effect.

2. Let AB be a double *concave* lens, then by tracing the progress of the ray ED, DD′, D′F, it will be seen that the effect of each surface of the lens is to cause the ray to diverge farther from the axis.

Fig. 276.



893. *In a double convex, or double concave lens, there is a certain point called its center, through which every ray that passes, has its incident and emergent rays parallel.*

Fig. 277.

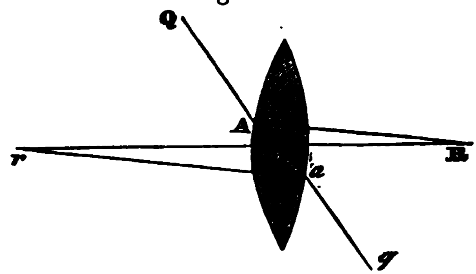
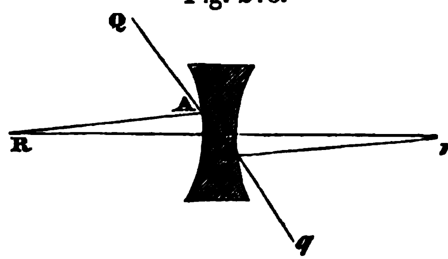


Fig. 278.



Let R*r* (Figs. 277, 278.) be the centers of the surfaces of these lenses, and RE*r* their axes. Draw any two of their radii RA, *ra*, parallel to each other, and join A*a*; the point E where this line intersects the axis will be the point above described. For since the triangles REA, *rea* are similar, $RA : ra :: RE : rE$, $RA \pm ra : ra :: RE \pm rE : rE$. And, as the three first terms of this proportion are invariable, the last, *r*E, must also be invariable. Hence it follows, that to whatever points in the surface of the lens, the parallel radii RA, *ra* are drawn, the line A*a*, produced if necessary, will always cut the axis R*r* in the same point E. If we now suppose the ray A*a* to pass both ways out of the lens, it will be refracted equally and in contrary directions; because RA, *ra* being perpendiculars to the surface at A and *a*, the angles of incidence of the ray A*a* or *a*A will be equal. Consequently, AQ will be parallel to *aq*. When the thickness of the lens is inconsiderable, and when a ray falls nearly perpendicularly upon it, the part of the ray through E, viz. QAE*aq*, may be taken as a straight line, passing through the center E of the lens; for the perpendicular distance between AQ, *aq* diminishes, both with the thickness of the lens, and with the obliquity of the ray to the axis.

894. The office of a convex lens is to *collect* rays of light. Hence, when applied to parallel rays, it makes them converge; to

diverging rays, it makes them diverge less; and to converging rays, it makes them converge more. Moreover, with regard to diverging rays, the degree of divergence may be reduced so much as to render the rays parallel, or even to make them converge, which will depend both on the position of the radiant, as illustrated in Art. 890, and on the power of the lens.

On the contrary, the office of a concave lens is to *separate* rays of light. Hence, when it is applied to parallel rays, it makes them diverge; to rays already diverging, it makes them diverge more; and to converging rays, it makes them converge less, become parallel, or even diverging.

895. With these general principles in view, we may now advantageously investigate the manner in which images are formed by means of lenses.

1. If we place a radiant, as a candle, nearer to a lens than its pricipal focus, then, since the rays go out diverging, (Art. 890.) no image will be formed on the other side of the lens.

2. If we place the radiant in the focus, the rays will go out parallel, but will still not be collected into a distinct image.

3. If the radiant is removed farther from the lens than its principal focus, then the rays will be collected on the other side of the lens so as to form a distinct representation of the object.

As this last case is particularly important, since it exhibits the manner in which images are formed by means of convex lenses, let us examine it with more attention.

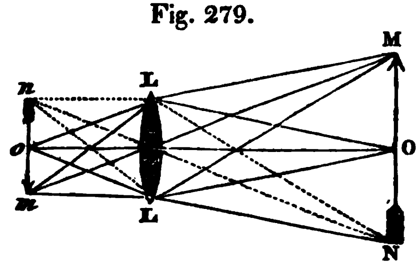
896. *Rays of light diverging from the several points of any object, which is farther from a convex lens than its principal focus, will be made to converge on the other side of the lens to points corresponding to those from which they diverged, and will form an image.*

Let MN (Fig. 279.) be a luminous object placed before a double convex lens L L. Now every point in the radiant sends forth innumerable rays in every direction, part of which fall upon the lens L L. Each pencil may be considered as a cone of rays, having for its axis the straight line which passes through the center of the lens, which line suffers no change of direction, (Art. 893.) while those rays of the pencil which strike upon the extreme parts of the lens, form the exte-

rior rays of the cone: all the others are of course included between these. It will be sufficient to follow the course of the central and the two extreme rays. Let ML, MC, ML represent such a pencil. The two extreme rays will be collected by the lens and made to meet in the axis or central ray in some point on the other side, as at *m*. For the same reason, every other point in the object will have its corresponding point in the image, and all these points of the image taken together, form a true representation of the object. By inspecting the figure, it will be seen that the axes of all the pencils cross each other in the center of the lens; that the image corresponding to the top of the object is carried to the bottom of the image, while that corresponding to the bottom of the object is at the top of the image, and, consequently, that the image is inverted with respect to the object. It will be farther seen, that although the individual rays which make up a single pencil are made, on passing through the lens, to converge, yet the axes of all the pencils go out diverging from each other, which carries them farther and farther asunder, the farther they proceed before they come to a focus. Hence, the farther the image is formed behind the lens, the greater will be its diameter, a principle which may be enunciated and proved as follows:

The diameter of the object is to the diameter of the image, as the distance of the object from the lens is to the distance of the image from the lens.

Fig. 279.



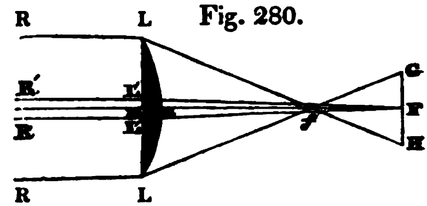
For the two triangles MOC and *mo*C are similar; therefore MO : *mo* :: CO : C*o*. With a given object, the diameter of the image is as its distance from the lens. And, since the surfaces of the object and the image are similar figures, (being parallel sections of similar pyramids or cones whose vertices meet in the center of the lens) the surface of the image is as the square of its distance from the lens. By bringing the object nearer to the lens, the image recedes from it on the other side, since the rays, being more divergent, are not so soon brought to a focus; therefore, by bringing the radiant very near to the focus of parallel rays, so as

to throw the image very far back, the latter becomes exceedingly magnified.

The diameter of the image will not be altered by changing the area of the lens: for that diameter will be determined in all cases by the distance between the *axes* of the two pencils which come from the extremities of the object and cross each other in the center of the lens. The size of the image, however will be affected by changing *the convexity of the lens*, while the object remains the same and at the same place.

897. *Rays proceeding from any radiant point which are refracted by the different parts of the same lens, do not meet accurately in one focus, but their points of meeting are spread over a certain space, whose diameter is called the* SPHERICAL ABERRATION *of the lens.*

Fig. 280.



Let LL be a plano-convex lens, on which are incident the parallel rays RL, RL at the extremities, and R′ L′, R′ L′ near the axis, according to Art. 882, the axis will proceed on without any change of direction, and the rays which are very near to the axis, being also nearly perpendicular to the refracting surface, sustain only a slight change of direction, sufficient, however, to collect them into a focus at some distance from the lens in the point F. But the rays RL, RL, meeting the refracting surface more obliquely, are more turned out of their course, and are therefore collected into a focus in some point nearer to the lens than F, as at *f*. The intermediate rays refracted by the lens will have their foci between F and *f*. Continue the lines L*f* and L*f*, till they meet at G and H a plane passing through F. The distance *f*F is called the *longitudinal spherical aberration*, and GH the *lateral spherical aberration.*

It is obvious that such a lens cannot form a distinct picture of any object in its focus F. If it is exposed to the sun, the central parts of the lens L′*m*L′, whose focus is at F, will form a pretty bright image of the sun at F; but as the rays of the sun which pass through the outer part LL of the lens have their foci at points between *f* and F, the rays will, after arriving at these points, pass on to the plane

GH, and occupy a circle whose diameter is GH; hence the image of the sun in the focus F will be a bright disk, surrounded and rendered indistinct by a broad halo of light growing fainter and fainter from F to G and H. In like manner every object seen through such a lens, and every image formed by it, will be rendered confused and indistinct by spherical aberration.

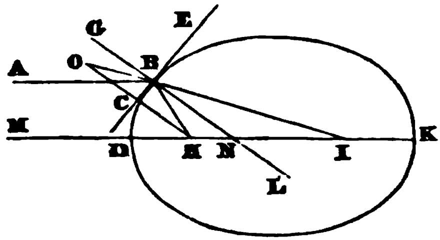
If we cover up all the exterior portions of the lens, so as to permit only those portions of the rays which lie near the axis to pass through the lens, then the rays all meet at or very near to the point F, and a much more distinct image is formed; but so much of the light is excluded by this process, that the brightness of the image is considerably diminished.—The *dimensions* of the image are the same in both cases. (Art. 896.)

898. By experiments made with different kinds of lenses, the following results are obtained. In *plano-convex* lenses placed as in Fig. 280, the greatest spherical aberration is $4\frac{1}{2}$ times $m\,n$ the thickness of the lens. In a *plano-convex* lens with its convex sides turned towards the parallel rays, the aberration is only $1\frac{17}{100}$ths of its thickness. In using a plano-concave lens, therefore, it should always be so placed, that the parallel rays should be incident upon the convex surface. In a *double convex* lens with equal convexities, the aberration is $1\frac{67}{100}$ths of its thickness. The lens which has *the least spherical aberration*, is a double convex one, whose radii are as 1 to 6. When the face whose radius is 1, is turned towards the parallel rays, the aberration is only $1\frac{7}{100}$ths of its thickness. Hence the lenses employed in optical instruments are made *very thin*; and the light is suffered to pass only through *the central parts* of the lens. As the central parts of the lens LL, refract the rays too little, and the marginal parts too much, it is evident that if we could increase the convexity at n, and diminish it gradually towards L, we should remove the spherical aberration. But the ellipse and hyperbola are curves of this kind, in which the curvature diminishes from n to L; and mathematicians have shown how spherical aberration may be entirely removed, by lenses whose sections are ellipses or hyperbolas. Of a lens of this kind we will annex one example.

899. *A lens in the form of a spheroid (generated by the revolution of an ellipse about its major axis) whose major axis is to the distance*

between its foci, as the sine of incidence to the sine of refraction, will cause parallel rays incident in the direction of its axis, to converge accurately to the remoter focus.

Fig. 281.



Let BDK be the generating eclipse, H and I its foci; then, by the supposition,

DK : HI : : *sin* Incidence : *sin* Refraction.

Let AB which is parallel to DK, be a ray of light incident upon the spheroid. Join HB, IB; draw EBC touching the generating eclipse in B; through B and H, draw GBL and HCO at right angles to EBC; let GBL meet DK in N; and produce IB till it meets HCO in O. Then, since HBC=IBE* and OBC=IBE, therefore HBC=OBC. Also BCH, BCO, are right angles, and BC is common to the two triangles BCH, BCO; therefore BO=BH and IO=DK; consequently,

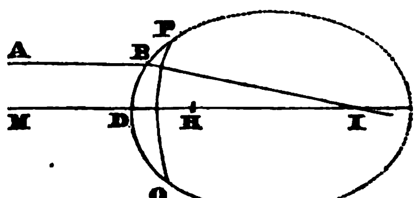
IO : IH : : *sin* : Incidence : *sin* Refraction. And because BN is parallel to OH,

IB : IN : : IO : IH : : *sin* Incid. *sin* Refrac.

Also, IB : IN : : *sin* INB : *sin* IBN : : *sin* BNH or *sin* ABG : *sin* IBL; therefore, *sin* ABG : *sin* IBL : : *sin* Incid. : *sin* Refrac. And since *sin* ABG is the sine of incidence, *sin* IBL is the sine of refraction; and because the angle LBI is less than a right angle, BI is the refracted ray. In the same manner it may be shown, that every other ray in the pencil will be refracted to I.

Cor. If from the center I, with any radius less than ID, a circular arc PQ be described, the solid generated by the revolution of P DQ about the axis DI, will refract all the rays incident parallel to DI, accurately to I. For, after refraction at the surface PDQ, the rays

Fig. 282.



* Conic Sec.

converge to I; and they suffer no refraction at the surface PQ, because they are incident perpendicularly upon it.*

900. Hence it follows, that a *meniscus* whose convex surface is part of an ellipsoid, and whose concave surface is part of any spherical surface whose center is in the farther focus, will have no spherical aberration, and will refract parallel rays incident on its convex surface to the farther focus. When the foregoing properties of the ellipse were discovered (and similar properties belong to the hyperbola) philosophers exerted all their ingenuity in grinding and polishing lenses with elliptical and hyperbolical surfaces, and various ingenious mechanical contrivances were proposed for this purpose. These, however, have not succeeded; and the difficulty of grinding glasses of any other than a spherical curvature, is such as to prevent the use of spheroidal and other forms not subject to aberration; but other expedients have been devised for correcting this error.

Though we cannot remove or diminish the spherical aberration of *single* lenses beyond $1\frac{7}{100}$ths of their thickness, yet by combining two or more lenses, and making opposite aberrations correct each other, we can remedy this defect to a very considerable extent in some cases, and in other cases remove it altogether.† The manner in which this is effected, will be more particularly pointed out in connexion with the subject of Microscopes and Telescopes.

CHAPTER V.

OF THE DECOMPOSITION OF LIGHT AND THE SOLAR SPECTRUM.‡

901. In tracing the course of rays of light through a refracting medium, we have thus far supposed them to be homogeneous, and to be all affected in the same manner. But in nature the fact is otherwise; that is,

* Wood's Optics, Sec. 187, 188.

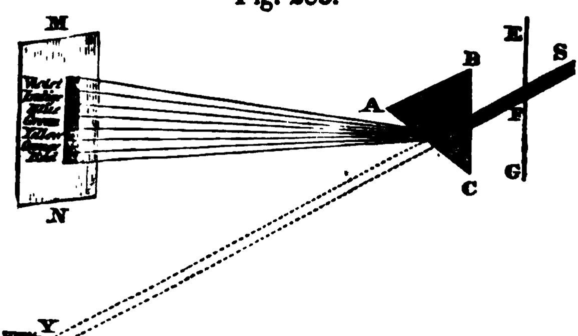
† Brewster.

‡ That part of Optics which treats of colors, is sometimes denominated *Chromatics*.

The sun's light consists of rays which differ in refrangibility and in color.

The glass prism, in consequence of the strong refraction of light which it produces, (see Art. 885.) is well fitted for experiments of this kind. We procure, therefore, a triangular prism of good flint glass, and having darkened a room, admit a sun beam obliquely through a small round hole in the window shutter. Across this beam, near the shutter, we place the prism, with its edge parallel to the horizon, so as to receive the beam upon one of its sides. The rays, on passing through the prism, will be refracted and thrown upwards, as will be rendered evident by conceiving perpendiculars drawn to the surface of the prism at the points of incidence and emergence. If now we receive the refracted rays upon a screen, at some distance, they will form an elongated image, exhibiting the colors of the rainbow, namely, red, orange, yellow, green, blue, indigo, violet, together composing the *prismatic spectrum.* (See Fig. 283.)

Fig. 283.



S, a sun-beam.

F, a hole in the window shutter.

ABC, the prism, having its refracting angle ACB downwards.

Y, a white spot, being an image of the sun formed on the floor before the prism is introduced.

MN, the screen containing the spectrum.*

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* The opposite white wall of plaster or stucco, may serve the purpose of a screen; or the screen may be made of a large sheet of white

902. On viewing the spectrum attentively, we perceive that the lowest or least refracted extremity is a brilliant red, more full and vivid than can be produced by any other means, or than the color of any natural substance. This dies away, first into an orange, and then passes by imperceptible gradations into a fine pale straw-yellow, which is quickly succeeded by a pure and very intense green, which again passes into a blue, at first of less purity, being mixed with green, but afterwards, as we trace it upwards, deepening into the purest indigo. Meanwhile, the intensity of the illumination is diminishing, and in the upper portions of the indigo tint, it is very feeble; but it is continued still beyond, and the blue acquires a pallid cast of purplish red, a livid hue better seen than described, and which, though not to be exactly matched by any natural color, approaches most nearly to that of a fading violet.*

A pleasing way of exhibiting the separate colors of the spectrum, is to throw the prismatic beam on a distant wall or screen, so as to form a long spectrum, and into this beam, at some convenient distance from the prism, to introduce a concave lens of a size sufficient to cover each of the different colored pencils successively. The lens will cause the rays of the same color to diverge, and to form a circular image on the screen, which will distinguish them very strikingly from the contiguous portions of the spectrum.

903. *If rays of the same color in the prismatic beam be insulated from the rest and made to pass through a second prism, they are refracted as usual, (the amount of refraction being different for the different colored rays,) but they undergo no farther change of color.*

To perform this experiment, we provide a board, perforated with a small round hole, and mounted on a stand. This screen is placed across the prismatic beam, a little way from the prism, in such a manner as to permit rays of the same color only to pass through the aperture, while the other portions of the beam are intercepted. The

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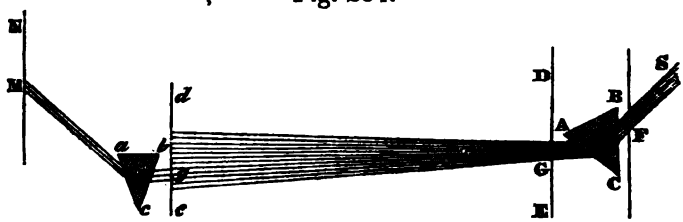
paper; but a convenient screen for the lecture room is made by pasting a large sheet of drawing paper to a frame and attaching it to a movable stand.

* Herschel on Light.

homogeneous light thus insulated is made to pass through a second prism, and its image is thrown on the wall. The experiment will be more perfect, if the homogeneous pencil be made to pass through a second screen similar to the first, so as to let only the central rays fall upon the second prism. This second refraction produces no change of color. It will be found, however, that, while all other things remain the same, the several images formed of homogeneous rays, will occupy different positions on the wall, the red being lowest and the violet highest, and the intermediate colors arranged between them in the order of their refrangibilities. (See Fig. 284.)

Fig. 284.



In addition to the parts of the figure enumerated in Fig. 283, DE represents the first screen, which permits only one sort of rays to pass by a small aperture at G, and *d e* represents a second screen, which permits only the central rays of this pencil to pass by a small hole at *g; abc* is the second prism, and M is the image of homogeneous light on the wall.

904. ***The light of the sun reflected from the first surface of bodies, and also the white flames of all combustibles, whether direct or reflected, differ in color and refrangibility, like the direct light of the sun.***

The truth stated in this proposition was established by Newton, by experiments with the prism, similar to those detailed in connexion with the preceding propositions.

905. ***The sun's light is compounded of all the prismatic colors, mixed in due proportion.***

If we collect, by means of a convex lens, the different colored pencils in the prismatic beam, just after they have emerged from the

prism, (see Fig. 283.) the image formed by the lens will be perfectly white. A concave mirror may be used instead of the lens, the image being thrown on a screen. Or the rays after they have passed the prism may be received on a second prism of the same kind, placed near the first, but with its refracting angle in the opposite direction. In this case the second prism restores the light to its usual whiteness.

That all the different colors of the spectrum are essential to the composition of white light, may be rendered evident by intercepting a portion of any one of the colors of the spectrum before they have been re-united as in the foregoing experiments. Thus if we introduce a thread or a wire into any part of the prismatic beam between the prism and the lens, the image formed by the lens will be no longer white but discolored. If, instead of the wire, an instrument, shaped like a comb with coarse broad teeth, be introduced into the beam, the discoloration of the image is more diversified, the colors of the image being those compounded of the prismatic colors, which are not intercepted by the comb. If the teeth of the comb be passed *slowly* over the beam, a succession of different colors appears, such as red, yellow, green, blue and purple; but if the motion of the comb be rapid, all these different hues become blended into one by the momentary continuance of each in the eye, and the sensation is that of white light. (See p. 218.)

906. For a similar reason, if the colors of the spectrum are painted on a top, in due intensity and proportion, and the top be set to spinning, the sensation will be that of white light. Or the colors of the spectrum may be first laid on a sheet of paper, and this may be pasted on a cylinder of wood, which may be made to revolve on the whirling tables: the result will be the same.—Newton tried various experiments with different colored powders, grinding together such as corresponded as nearly as possible to the colors of the spectrum. By these means he was able to produce, from the mixture of seven different colored powders, a *greyish-white*, but could never reach a perfectly clear white, owing to the difficulty of finding powders whose colors corresponded exactly to those of the spectrum.

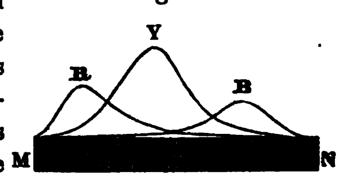
907. *Several of the colors of the spectrum may be produced by the mixture of other colors; as green by the union of yellow and blue, orange by red and yellow, &c.*

Experiments were devised by Newton for thus combining the colors of two contiguous spectrums, transferring, for example, the blue of one to the yellow of the other, and and forming green by their union. On causing this compound green, however, to pass through the prism, it is resolved into its original colors, yellow and blue, whereas, the green of the spectrum is not thus resolved by the prism. Hence Newton infers that the green of the spectrum is not a compound but a simple original color, and so of all the rest.

908. It has, however, been a question among opticians since the time of Newton *what is the number of original or fundamental colors in the spectrum?* Many years since, Mayer advanced the hypothesis that the only simple colors in the solar spectrum are *red, yellow* and *blue*—all the others being compounded of these; and more recently Dr. Brewster has gone far towards establishing this doctrine. According to this eminent optician, (1.) Red, yellow, and blue light exist at every point of the solar spectrum; (2.) As a certain portion of red, yellow, and blue, constitute *white* light, the color of every point of the spectrum may be considered as consisting of the predominating color at any point, mixed with white light. Thus, in the red space there is *more red* than is necessary to make white light with the small portions of yellow and blue which exist there; in the yellow space there is *more yellow* than is necessary to make white light with the red and blue; and in the part of the blue space which appears violet, there is more red than yellow, and hence the excess of red forms a violet with the blue.

909. The mode by which these three primary colors produce by their combination the seven colors developed by the prism, is exhibited to the eye by the following diagram. MN is the prismatic spectrum, consisting of three primary spectra of the same length, viz. a red, a yellow, and a blue spectrum. The intensities of each color at various points of the spectrum, are represented by ordinates of different lengths the extremities of which form the curves MRN, MYN, and MBN, corresponding to the three colors red, yellow and blue respectively. The *red* spectrum has its maxi-

Fig. 285.



mum intensity at R; and this intensity may be represented by the distance of the point R from MN. The intensity declines rapidly to M and slowly to N, at both of which points it vanishes. The *yellow* spectrum has its maximum intensity at Y, the intensity declining to zero at M and N; and the *blue* has its maximum intensity at B, declining to nothing at M and N. The general curve which represents the total illumination at any point, will be outside these three curves, and its ordinate at any point will be equal to the sum of the three ordinates at the same point. Thus the ordinate of the general curve at the point Y, will be equal to the ordinate of the yellow curve, which may be supposed to be 10; added to that of the red curve which may be 2, and that of the blue, which may be 1. Hence the general ordinate will be 13. Now if we suppose that three parts of yellow, two of red, and one of blue make white, we shall have the color at Y equal to $3+2+1=6$ parts of white mixed with seven parts of yellow; that is, the compound tint at Y will be a bright *yellow*, without any trace of red or blue. As these colors all occupy the same place in the spectrum, they cannot be separated by the prism; and if we could find a colored glass, which would absorb seven parts of the yellow, we should obtain at the point Y, a *white light*, which the prism could not decompose.*

910. The arguments on which most of these conclusions are grounded, are derived from experiments on the analysis of light by *absorption*. If (says Dr. Brewster) we take a piece of blue glass, and transmit through it a beam of white light, the light will be of a fine deep blue. This blue is not a simple homogeneous color, like the blue or indigo of the spectrum, but is a mixture of all the colors of white light which the glass has not absorbed; and the colors which the glass has absorbed are those which the *blue wants* of white light. In order to determine what these colors are, let us transmit through the blue glass, the prismatic spectrum KL, Fig. 283; or, what is the same thing, let the observer place his eye behind the prism BAC, and look through it; he will see the spectrum on the other side of the prism, but with this remarkable change, that it will appear deficient

* Brewster's Treatise on Optics, p. 73.

in a certain number of its differently colored rays. A particular thickness absorbs the middle of the red space, the whole of the orange, a great part of the green, a considerable part of the blue, a little of the indigo, and a very little of the violet. The yellow space, which has not been much absorbed, has increased in breadth. It occupies part of the space formerly covered by the *orange* on one side, and part of the space formerly covered by the *green* on the other. Hence it follows that the blue glass has absorbed the red light which, when mixed with the yellow light, constituted *orange*, and has absorbed also the *blue* light, which when mixed with the yellow, constituted a part of the green space next to the yellow. We have, therefore, by absorption, decomposed *green* light into yellow and blue, and *orange* light into yellow and red; and it consequently follows, that the orange and green rays of the spectrum, though they cannot be decomposed by prismatic refraction, can be decomposed by absorption, and actually *consist of two different colors possessing the same degree of refrangibility*. Difference of color is therefore not a test of difference of refrangibility; and the conclusion deduced by Newton is no longer admissible as a general truth: "That to the same degree of refrangibility ever belongs the same color, and to the same color ever belongs the same degree of refrangibility."

By absorbing the excess of any color at any point of the spectrum above what is necessary to form white light, we may actually cause white light to appear at that point, and *this white light will possess the remarkable property of remaining white after any number of refractions, and of being decomposable only by absorption.*

Fixed Lines in the Spectrum.

911. The solar spectrum, in its greatest possible state of purity and tenuity, when received on a white screen, or when viewed by admitting it at once into the eye, is not an uninterrupted line of light, red at one end and violet at the other, and shading away by insensible gradations through every intermediate tint from one to the other, as Newton conceived it to be, and as a cursory view shows it. *It is interrupted by intervals absolutely dark;* and in those parts where it is luminous, the intensity of the light is extremely irregular and capricious, and apparently subject to no law, or to one of the utmost

complexity. In consequence, if we view a spectrum formed by a narrow line of light parallel to the refracting edge of the prism, (which affords a considerable breadth of spectrum without impairing the purity of the colors, being, in fact, an assemblage of infinitely narrow linear spectra arranged side by side,) instead of a luminous fascia of equable light and graduating colors, it presents the appearance of a striped ribband, being crossed in the direction of its breadth by an infinite multitude of dark, and by some totally black *bands*, distributed irregularly throughout its whole extent. This irregularity, however, is not a consequence of any casual circumstances. The bands are constantly in the same parts of the spectrum, and preserve the same order and relations to each other; the same proportional breadth and degree of obscurity, whenever and however they are examined, *provided solar light be used*, and provided the prisms employed be composed of the same material: for a difference in the latter particular, though it causes no change in the number, order, or intensity of the bands, or their places in the spectrum, as referred to the several colors of which it consists, yet causes a variation in their proportional distance from one another. By solar light must be understood, not merely the direct rays of the sun, but any rays which have the sun for their ultimate origin; the light of the clouds, or sky, for instance; of the rainbow; of the moon or of the planets. All these lights, when analyzed by the prism, are found deficient in the identical rays which are wanting in the solar spectrum; and the deficiency is marked by the same phenomenon, viz. by the occurrence of the same dark bands in the same situations in spectra formed by these several lights. In the light of the stars, on the other hand, in electric light, and in that of flames, though similar bands are observed in their spectra, yet they are differently disposed; and the spectrum of each several star, and each flame, has a system of bands peculiar to itself, and characteristic of its light, which it preserves unalterably at all times, and under all circumstances.

912. Fig. 286 is a representation of the fixed lines of the spectrum, according to Fraunhofer,* the small bands observed by him (more than five hundred in number) being omitted. Of these fixed

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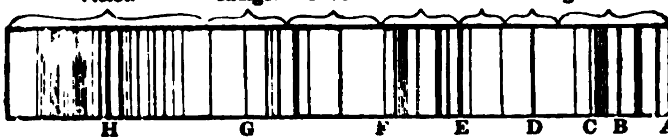
* A celebrated German optician, recently deceased.

Fig. 286.



lines, he selected seven, (those marked B, C, D, E, F, G, H,) as terms of comparison, or as standard points of reference in the spectrum, on account of their distinctness, and the facility with which they may be recognised. The definiteness of these lines, and their fixed position, with respect to the colors of the spectrum,—in other words, the precision of the limits of those degrees of refrangibility which belong to the *deficient* rays of solar light,—renders them invaluable in optical inquiries, and enables us to give a precision hitherto unheard of to optical measurements, and to place the determination of the refractive powers of media on the several rays almost on the same footing, with respect to exactness, with astronomical observations.*

CHAPTER VI.

OF COLORS IN NATURAL OBJECTS.

913. The knowledge of the composition of light, and of the properties of the solar spectrum, naturally led to an inquiry into the subject of colors, as exhibited in the phenomena of nature. The bright tints of the rainbow, the splendid hues sometimes exhibited by thin plates, as soap bubbles, and finally the diversified colors of objects in all the kingdoms of nature, remained to be accounted for. We propose now to inquire how far this object has been effected.

The Rainbow.

914. The rainbow, one of the most striking and magnificent of the phenomena of nature, was long ago supposed to be owing to

* Herschel on Light.

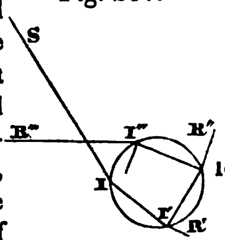
some modification which the light of the sun undergoes in passing into drops of rain, but the complete development of the causes on which it depends, was reserved for the genius of Newton, and naturally followed in the train of those discoveries which he made upon the prismatic spectrum.

The rainbow, when exhibited in its more perfect forms, consists of two arches, usually seen in the east during a shower of rain, while the sun is shining in the west. These arches are denominated the outer and the inner bow, of which the inner bow is the brighter, but the outer bow is of larger dimensions every way. The succession of colors in the one is directly opposite to that of the other.

915. Drops of rain, though small, are large in comparison with the minuteness of rays of light, and are to be regarded as spheres of water, exerting the powers of refraction and reflexion in the same manner as large globes of water would do. It was, in fact, by investigating the manner in which globular glass vessels filled with water modify the solar rays, that the first hints were obtained respecting the cause of the rainbow. In the year 1611, Antonio de Dominis made a considerable advance towards the theory of the rainbow, by suspending a glass globe in the sun's light, when he found that while he stood with his back to the sun the colors of the rainbow were reflected to his eye in succession by the globe, as it was moved higher or lower.

Let us, therefore, in the first place, follow the course of a ray of light through a globule of water. Let SI (Fig. 287.) be a small beam of light from the sun, falling upon the surface of a globule of water at I. Agreeably to what is known of the laws of light in passing out of one transparent medium into another, a portion of the rays would be reflected at I, and another portion would pass into the drop and be refracted to the farther surface at I′. The same effect would recur here, and also at I″, and at I‴; and were the eye situated in either of the lines I′R′, I″R″, or I‴R‴, it would perceive the prismatic colors, because some of the rays which composed the beam of light that reached the eye, would be refracted more than others, and

Fig. 287.



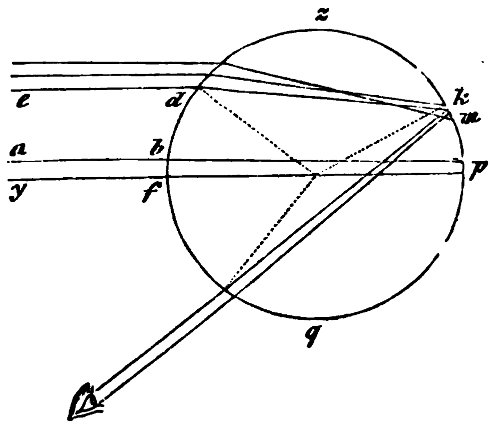
thus the different colors would be made to appear. Or if a screen were so placed as to receive these transmitted rays, a faint spectrum would be formed upon it. Such a progress of a beam of light admitted through the window shutter, and made to fall on a globular vessel of water, may be actually rendered visible by experiment.*

916. It may be remarked that but a comparatively small part of the solar rays that shine upon a drop of water, are required in order to produce the mild light of the rainbow, aided as its light is by the dark ground or cloud on which it is usually projected; yet where the number of rays that enter the eye is diminished beyond a certain limit, the light becomes too feeble for distinct vision. It will also be observed, that a considerable portion of light is lost at each successive reflexion that takes place within the drop, so that a certain beam of light, conveyed to the eye after two reflexions, will be much more feeble than the same beam after one reflexion. Indeed, so much of the sun's light is dissipated at the first point of reflexion from the interior surface, added to what is transmitted at the same point, and of course never reaches the eye of the spectator, that, were it not for a great *accumulation* which the sun's rays undergo at a particular point in this drop, whence the light is reflected and conveyed to the eye, the phenomena of the rainbow would not occur. The manner in which this accumulation is effected, is now to be explained.

917. Let $f z p q$ (Fig. 288.) be the section of a drop of rain, $f p$ a diameter, $a b$, $c d$, &c. parallel rays of the sun's light, falling upon the drop. Now $y f$, a ray coinciding with the diameter, would suffer no refraction; and $a b$, a ray near to $y f$, would suffer only a very small inclination towards the radius, so as to meet the remoter surface of the drop very near to p; but the rays which lie farther from $y f$, being inclined towards the radius in a greater angle, would be more and more refracted as they were farther removed from the diameter. The consequence would be, that after passing a certain limit, the rays that lay above that limit would cross those which lay

* Biot.

Fig. 288.

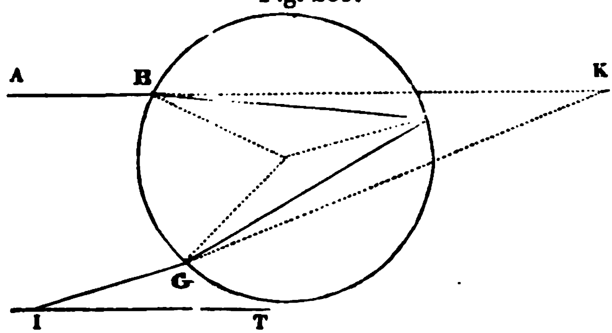


below it and meet the further surface somewhere between the diameter and the ray which passed through the said limit; that is, all the rays falling on the quadrant fz, would meet the circumference within the arc kp. But when a quantity is approaching its limit, or is beginning to deviate from it, its variations are nearly insensible. Thus, when the sun is at the tropics, being the limits to which he departs from the equator, he appears for some time to remain at the same point. In the same manner, a great number of the rays which lie contiguous to ed, on both sides of it, will meet in very nearly the same point on the concave surface of the drop at km. Consequently, a greater number of rays will be reflected from that point than from any other in the arc. Moreover, proceeding from a single point, they will emerge parallel, and therefore more of them will enter an eye favorably situated, than if they passed out diverging. On both these accounts, it appears, that there is a particular point in a drop of rain, where the rays of the sun's light seem to *accumulate*, and are therefore peculiarly fitted to make an impression on the organ of vision. It is found by calculation that the angle which the incident and emergent rays, in such cases, make with each other, is, for the *red* rays 42° 2′, and for the *violet* rays 40° 17′. These are the angles when the rays emerge after two refractions and *one* reflexion: in the case of two refractions and *two* reflexions, the angles are, for the *red* rays 50° 59′, and for the *violet* 54° 9′.

918. Let us next consider what must be the position of the spectator in order that his eye may receive the emergent rays which make the foregoing angle with the incident rays, and which of course are those which cause the phenomena of the rainbow.

The spectator must stand with his back to the sun, and *a line drawn from the sun towards the bow so as to pass through his eye, will make the same angle with the emergent rays that they make with the incident rays*. Thus let AB be the incident and GI the emergent

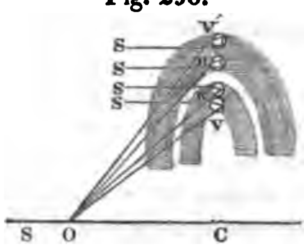
Fig. 289.



ray and let the angle which these two rays make with each other be AKI; and let IT be a ray passing from the sun towards the bow through the eye of the spectator; then, (since the rays of the sun may be regarded as parallel,) AB and IT are parallel, and the alternate angles AKI and KIT, equal. But AKI is the angle made by the incident and emergent rays, and KIT the angle made by the emergent ray, and a line drawn from the sun towards the bow through the eye of the spectator.

919. *When the sun shines upon the drops of rain as they are falling, the rays which come from those drops to the eye of the spectator after* ONE REFLEXION AND TWO REFRACTIONS, *produce the innermost or primary rainbow; and those drops which come to the eye after two* REFLEXIONS AND TWO REFRACTIONS, *produce the outermost or superior rainbow.*

Fig. 290.



Let SOC* be a straight line passing from the center of the sun through the eye of the spectator at O towards the bow, and let SR, SV be incident rays which after one reflection and and two refractions are conveyed to the eye at O, making (Art. 918.) with SOC angles equal to those formed by the incident and emergent rays. If OV makes with SOC an angle of 40° 17′, and be conceived to revolve around OC, describing the surface of a cone, all the drops of rain on this surface will be precisely in the situation necessary in order that the violet rays, after two refractions and one reflexion, may emerge parallel and arrive at the eye in O, and this will not take place in the same manner on any other part of the cloud; so that by means of this species of rays, the spectator will see on the cloud a violet colored arc, of which OC will be the axis, and C the center. He will besides, see also an infinity of other concentric arcs exterior to the violet, each one of which will be made up of a single species of rays; and according as these rays are less refrangible, their areas will be of greater diameter, so that the largest, composed of the extreme red will subtend an angle ROC of 42° 2′. Therefore the whole width of the colored bow will be 42° 2′—40° 17′, or 1° 45′, the red being on the outside and the violet within.

The contrary order of colors will result from *two reflexions* and two refractions. Let SV′, SR′, be the incident rays, which after two reflexions and two refractions are converged to the eye at O, making (Art. 918.) with SOC angles equal to those formed by the incident and emergent rays, namely 50° 59′ and 54° 9′, and the lines RO′ and VO′, as before, be conceived to revolve around SOC; they will severally meet with all the drops which having twice refracted and twice reflected the extreme red and violet rays, can transmit them to the eye parallel to each other. Between these two arcs, there will be others exhibiting all the intermediate prismatic

* It will be observed that the line SOC is at right angles to the plane of the surface, that is, to the plane of the bows.

colors; and the whole together will form a second bow, whose breadth will be 54° 9′—50° 59′ or 3° 10′.

920. The rays therefore which come from all the drops which make an angle of 42° 2′ with a line passing from the sun through the eye (which may be called the *axis of vision*) appear red; and it is obvious that a collection of rays drawn all around this axis from the eye to drops thus situated would form a cone, of which the drops themselves would constitute the base, and of course would form a circle. The same is true of all the other colors which emerge from drops at angles which are different for different colors but constant for the same color. Hence, *the line which passes from the sun through the eye of the spectator, passes also to the center of the bow*, or is the axis of the cone of which the bow itself is the base. If the sun is on the horizon, this axis becomes a horizontal line; consequently, the center of the arch rests on the opposite horizon, and the bow is a semi-circle, of which the highest point has an altitude above the horizon of 42° 2′. If the sun is at this altitude of 42° 2′ above the horizon, then the center of the bow will have the same depression below the opposite horizon, and the circumference, at its highest point will just reach that horizon. When the sun is between these two points, the elevation of the bow will be the difference between the altitude of the sun and the foregoing angle.

921. When the spectator is on an eminence, as a high mountain, he may see more than half the bow, when the sun is near setting; for the axis will in that case pass to a point above the opposite horizon. Travellers who have ascended very high mountains, have occasionally observed their shadows projected on the clouds below, with their heads encircled with rainbows.* In this case, the axis passes to a point above the opposite horizon equal to or greater than the semi-diameter of the bow, so that the whole of the circumference comes into view; and the eye of the spectator being in the axis, the entire bow is projected around that as a center, upon the surface of the clouds.

* Amer. Jour. of Science, Vol. XII. 172.—Malté Brun's Universal Geog. Vol. I. p. 363.

Colors of Bodies.

922. According to the Newtonian theory, the color of a body depends on *the kind of light which it reflects.* A great number of bodies are fitted to reflect at once several kinds of rays, and consequently appear under mixed colors. It may even happen that of two bodies which should be green, for example, one may reflect the pure prismatic green, and the other the green which arises from the mixture of yellow and blue. This quality of selection as it were in bodies, which varies to infinity, occasions the different kinds of rays to unite in every possible manner and every possible proportion; and hence the inexhaustible variety of shades which nature as in sport has diffused over the surfaces of different bodies.

When a body absorbs nearly all the light that reaches it, that body appears black: it transmits to the eye so few reflected rays, that it is scarcely perceptible in itself, and its presence and form make no impression on us, unless as it interrupts, in a manner, the brightness of the surrounding space.

923. But for a body to reflect one kind of ray rather than any other kind, there must be something in that body which determines the preference. In what then does a red body differ in this respect from a yellow, a green, or a violet one? Various attempts have been made, and on various hypotheses, to resolve this question. Newton, who entered on this subject with great earnestness, has here most successfully interrogated nature by a series of experiments, of which we shall give the results.

924. Having taken two glasses of a telescope, the one plano-convex, the other slightly convex on both sides, he placed one of the faces of this upon the plane face of the former, and pressed the two glasses at first gently, and then by degrees more closely against one another. The effect of this gradual pressure was, an appearance of *colored circles* in the plate of air between the glasses, which circles had the point of contact for a common center, and which increased in number as the pressure was increased, in such a manner that the circle which appeared last always surrounded the point of contact,

and on a still further pressure extended its circumference while it contracted itself breadthwise, to form a kind of ring round a new circle that arose near its middle.

The pressure having been carried to a certain term, Newton stopped and observed as follows: At the point of contact was a black spot that was encompassed by several series of colors, arranged from the center outwards in the following order:

First series, blue, white, yellow, red.

Second, violet, blue, green, yellow, red.

Third, purple, blue, green, yellow, red.

Fourth, green and red.

Fifth, greenish blue and red.

Sixth, greenish blue and pale red.

Seventh, greenish blue, and reddish white.

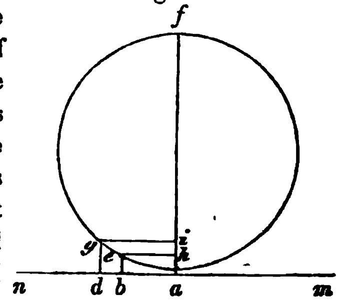
Beyond this number the tints were regularly paler until the color became white.

The reason why these successive colors were arranged in rings, having the point of contact of the two lenses for their common center is obvious, since each color was developed at a certain thickness, and the points of equal thickness being equidistant from the center, they would of course be arranged in the circumference of a circle.

Newton measured the diameters of the annular bands formed of these different colors, by taking the points where they had most lustre; and he found that the squares of those diameters were to one another as the terms of the ascending progression 1, 3, 5, 7, 9, 11, &c.; from which it results, that the intervals between the two glasses, relatively to the corresponding points, followed the same progression.

For let n, a, m (Fig. 291.) be a diameter taken on the surface of the plane glass, and a, g, f, a section of the sphere to which that part of the double convex lens that turns towards a, belongs. Let also ab, ad, be the semi-diameters of the two rings at the points where the colors are most vivid. Having drawn be, dg, parallel to the diameter af, and eh, gi, parallel to an, we shall have

Fig. 291.



$$(eh)^2 : (gi)^2 :: ah \times hf : ai \times if$$

But the distances between the two lenses being exceedingly small in comparison with the diameter af, hf and if may be taken as equal to af, whence, by substitution,

$$(eh)^2 : (gi)^2 :: ah \times af : ai \times af :: ah : ai :: be : dg$$

925. From these proportions, it was merely necessary to ascertain the absolute length of a single diameter, to know the lengths of all the others, as well as the different thicknesses of the plates of air at the points where the different colors were seen. Newton drew up a table of these degrees of thickness, assigning to each color that degree at which it was developed. For example, the most intense blue makes its appearance at a thickness equal to the 24th millionth part of an inch, the visual ray being supposed to come to the eye perpendicularly to the two glasses. As the visual rays deviate from a perpendicular, the breadth of the rings increases, the same color requiring a greater thickness to produce it. Among other results obtained from these experiments were the following:

Air, at and below a thickness of *half a millionth* of an inch, ceases to reflect light. At and above a thickness of *seventy two millionths* of an inch it reflects white, that is all the rays of the spectrum. Between these two limits it reflects the various orders of colors contained in the table.

Water, at and below a thickness of *three eighths of a millionth* of an inch ceases to reflect light. At and above *fifty eight millionths* of an inch it reflects white; and between these two limits, it reflects the orders of the colors contained in the table.

Glass, at and above *one third of a millionth* of an inch ceases to reflect light. At and above a thickness of *fifty millionths* of an inch it reflects white, and between these limits, it reflects the orders of colors contained in the table.

Newton also having measured the diameter of the rings at the intermediate places where the colors were obscure, found that their squares were to one another as the even numbers 2, 4, 6, 8, 10, 12, &c; and hence the intervals between the glasses, at the corresponding points, observed a similar progression.

926. Such were the phenomena which the glasses presented as seen by *reflexion*; but on looking through them to observe the effect of *refracted* light, other series of colors took place of the preceding ones. The central spot, which was before black, now became white, and the order of colors, relatively to the different series was this:

1. Yellowish red, black, violet, blue.
2. White, yellow, red, violet, blue.
3. Green, yellow, red, bluish-green.
4. 5. and 6. Red, bluish-green.

By comparing these colors seen by transmitted with those seen by reflected light, it is observable that the white answers to black, the red to blue, the yellow to violet, the green to a mixture of red and violet; that is, the part that appeared black on simply looking at the glasses became white when the observer looked *through* them, and so of the other colors. But the tints produced by transmitted light were feeble and languishing unless the visual ray was extremely oblique, in which case they were sufficiently vivid and brilliant.

927. Newton substituted water for air between the two glasses, and the colors instantly became fainter, and the rings contracted; that is, the ring of a particular color had its circumference nearer the center than when that color was reflected by the plate of air. The diameters of the corresponding rings were to one another nearly as 7 to 8, and consequently their squares were as 49 to 64; whence it follows, that the different thicknesses of the fluids at the places where the rings appeared, were nearly as 3 to 4, that is, in the ratio of the sine of incidence to the sine of refraction (Art. 881.) when the light passes from water into air. Newton imagined that this result might be extended to all kinds of mediums, and he therefore deduced from it this general law: that where a medium more or less dense than water is impressed between two glasses, the interval between the glasses at the place where any particular color is perceived, is to the interval which gives that color by means of air, as the sines which measure the refraction at the passage from the same medium into air. This rule may be equally applied to a thin plate, detached from any kind of body, the thickness of which we would determine by the tone of its color.*

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* Haüy, Nat. Philosophy, Sects. 711—720.

928. The phenomena of the rings being reduced to laws extremely exact and well adapted to calculation, Newton reduced them all to a still simpler expression, making them depend on a physical property which he attributed to light, and of which he defined all the particulars conformably to their laws. Considering light as a matter composed of small molecules emitted by luminous bodies with very great velocities, he concluded that since they were *reflected* within the lamina of air, at the several thicknesses corresponding to the numbers 1, 3, 5, 7, &c. and *transmitted* at the intermediate thicknesses 0, 2, 4, 6, &c. the molecules must have some peculiar modification of a periodical nature, such as to incline them alternately to be reflected and refracted after passing through certain spaces. Newton characterised this tendency to alternate reflexion and transmission, and designated the two states, by the phrases *fits of easy reflexion, and fits of easy transmission.**

929. Having defined completely all the characters of these fits, or *periodical returns of states favorable to reflexion and transmission,* Newton employed them as a simple property, not only to unite under one point of view the phenomena of the colors produced by thin plates, but also to foresee and to calculate beforehand, both as to their general tenor, and their minutest details, a crowd of analogous phenomena, observed to attend reflexion in thick plates, which, in fact, exceeded by as much as twenty or thirty thousand times those on which the calculations had been founded; moreover, applying the same reasoning to the integrant particles of material substances, which all chemical and physical phenomena show to be very minute, and to be separated even in the most solid bodies, by spaces immense in comparison of their absolute dimensions, he was able to deduce

* This phraseology has an air much more hypothetical than the reality, the thing signified being little more than the simple enunciation of a fact ascertained by experiment. Probably the singularity of the phrase, has contributed to bring the doctrine into discredit, or even into ridicule, with those who have never looked any farther into it than to read the title. The most profound opticians of modern times, have regarded these investigations of Newton, as among the most ingenious and sagacious of all his labors.

naturally from the same principles the theory of the different colors they present to us, a theory which adapts itself with a surprising facility to all the observations to which those colors can be submitted. The number and importance of those applications account sufficiently for the care which Newton bestowed on his experiments on colored rings.*

930. Among the experiments of Newton on colored rings, none are more interesting than those which he instituted on *soap bubbles*. It is well known, that when these bubbles are inflated to a certain degree of thinness, very gaudy colors make their appearance, and hence these are selected as favorite objects of amusement for children. But it was reserved for no less a mind than that of Newton, to make these exhibitions the means of penetrating the secrets of nature.

In preparing the bubbles for experiment, he took various ingenious precautions to form them in the most perfect manner, and preserved them for deliberate examination by covering them with a glass receiver which protected them from the agitation of the air, and means were devised for preventing any extraneous light from mixing with that of the bubble. Things being thus arranged, and the eye placed in a favorable position, a number of concentric horizontal rings are seen, exhibiting vivid colors disposed with perfect regularity. They correspond in appearance with those exhibited by the plate of air between the lenses, (Art. 924.) but are more elegant and perfect in every respect. Similar exhibitions of color are presented in glass bubbles blown exceedingly thin; and also in the thin laminæ of the mineral called mica. Analogous variations of color are seen even in the tarnish of certain metals, particularly in plates of copper and steel when they have been heated in the open air, and in the plumage of birds.

931. The following propositions, several of which have already been incidentally mentioned, will present a *summary* of the Newtonian doctrine of colors.

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* Biot.

1. The colors of natural bodies are not qualities inherent in the bodies themselves, by which they immediately affect our sight, but *are mere consequences of that peculiar disposition of the particles of each body, by which it is enabled more copiously to reflect the rays of one particular color, and to transmit, or stifle, or, more properly, to absorb, the others.*

2. The colors of natural bodies are the colors of *thin plates*, produced by the same cause as that which produces them in thin laminæ of air, glass, &c. viz. the interval between the interior and posterior surfaces of the atoms. The *thickness* of the atoms of a medium, and of the interstices between them, determines the color they reflect or transmit at a particular incidence, because it must depend on the thickness of any lamina, whether the light when it has reached its posterior surface is in the state favorable for transmission or for reflexion.

3. Opacity in natural bodies arises from the *multitude of reflexions* caused in their internal parts. By this means, the rays are conceived to be entangled, as it were, running their rounds from atom to atom, without a possibility of reaching the surface and escaping.

932. It would be inconsistent with the nature of an elementary work like the present, to enter into all the details of this remarkable hypothesis; for such disquisitions we must refer the student to Newton's Optics, to Biot's Traité de Physique, to Herschel's Treatise on Light, and to various other works of great ability which have been written on these subjects within the present century. All concur in speaking with the highest admiration, both of the depth and ingenuity of these researches of Newton. Herschel, for example, denominates it "a theory of extraordinary boldness and subtility, in which great difficulties are eluded by elegant refinements, and the appeal to our ignorance on some points is so dexterously backed by the weight of our knowledge on others, as to silence, if not refute, objections which at first sight appear conclusive against it.*

* Herschel on Light, Sec. 1134.

Inflexion or Diffraction of Light.

933. INFLEXION or DIFFRACTION *is a term used to denote certain phenomena, which light exhibits when it passes near the edges of bodies.*

For the purpose of experiments on this subject, a beam of light is admitted into a dark room, through a very small aperture, as a pin-hole made in sheet lead; or, what is better, a convex lens is placed in the window shutter, which brings the rays to a focus, and affords a divergent pencil of light. If we introduce into this pencil any opake body, as a knife-blade, for example, and observe the shadow which it casts on a white screen, we shall observe on both sides of the shadow *fringes of colored light*, the different colors succeeding each other in the following order: first fringe, *violet*, *indigo*, *pale blue*, *green*, *yellow*, *red;* second, *blue*, *yellow*, *red;* third, *pale blue*, *pale yellow*, *red*. The brightness of these fringes diminishes as they recede from the shadow, and the shadow itself is not quite dark, but is formed also of luminous and dark fringes, all parallel to the edges of the lamina. The fringes in question are absolutely independent of the nature of the body whose shadow they surround, and the form of its edge; neither the density or rarity of the one, nor the sharpness or curvature of the other, having the least influence on their breadth, their colors, or their distance from the shadow. Thus it is indifferent whether they are formed by the edge or back of a razor, by a mass of platina, or by a bubble in a plate of glass, (which, though transparent, yet throws a shadow by dispersing away the light incident upon it;) circumstances which make it clear that their origin has no connexion with the ordinary refractive powers of bodies, or with any *elective* attractions or repulsions exerted by them on light; for such forces cannot be conceived as independent of the *density* of the body exerting them, however minute we might regard the sphere of their action.*

934. If the light of the solar beam be first separated into the prismatic colors, and these severally be submitted to experiment, the fringes will in each case be of the same color as the colored pencil;

* Herschel.—Brewster, *Life of Newton*, p. 103.

but they will be broadest in *red* light, smallest in *violet*, and of intermediate sizes in the intermediate colors. If we place the screen at different distances from the interposed body which gives the shadow, it will be found that the fringes grow less and less as we approach the edge of the body from which they take their rise. On measuring the distances of the fringes from the shadow, while they are thus changing their dimensions, and connecting by a line the several points representing those distances, it is found that this line is not a straight line, but a *hyperbola*, whose vertex is at the edge of the body; so that the same fringe is not formed of the same light at all distances from the body, but resembles a caustic curve, (Art. 877.) formed by the intersection of different rays. When we consider that the fringes are largest in red, and smallest in violet light, it is easy to understand the cause of their colors in white light; for the colors seen in this case arise from the superposition of fringes of all the seven colors; that is, if the eye could receive all the seven differently colored fringes at once, these colors would form by their mixture the actual colors in the fringes seen by white light. Hence we see why the color of the first fringe is violet near the shadow, and red at a greater distance; and why the blending of the colors beyond the third fringe, forms white light, instead of exhibiting themselves in separate tints.

Upon measuring the proportional breadths of the fringes with great care, Newton found that they were as the numbers 1, $\sqrt{\frac{1}{3}}$, $\sqrt{\frac{1}{5}}$ $\sqrt{\frac{1}{7}}$, and their intervals in the same proportion.*

935. In the foregoing experiments, the colored fringes are supposed to be formed on the edge of the shadow of an opake body placed in a beam or pencil of light. The same phenomena are exhibited in a more striking and beautiful manner, when we view with a magnifying glass, a pencil of light as it passes through an exceedingly small aperture. Suppose, for instance, we place a sheet of lead, having a small pin-hole pierced through it, in the pencil of rays diverging from the focus of a lens, as in Art. 933. The image of the hole will be seen through the lens as a brilliant spot, encircled by rings of colors

* Brewster's Optics, pp. 95–97.

of great vividness, which contract and dilate, and undergo a singular and beautiful alternation of tints, as the distance of the hole from the luminous point on the one hand, or from the magnifier on the other, is changed. When the latter distance is considerable, the central spot is white, and the rings follow nearly the orders of colors of their plates. When the magnifier is brought very near to the pin-hole the central white spot contracts into a point and vanishes, and the rings gradually close in upon it in succession, so that the center assumes, successively, the most surprisingly vivid and intense hues, and the rings surrounding it undergo great and abrupt changes in their tints.*

Newton attempted to account for the inflexion of light by a supposed repulsion exerted by the edge of the interposed body, or by the edges of the circular aperture on the rays of light that are nearest to it, while they exert a less *repulsion* on such as are a little more remote. By this means, the relative direction of the rays would be so altered that they would cross one another, and their light interfere, or become blended; and by following out the consequences of this interference, they were found to correspond to some of the effects actually observed to take place.

936. A more satisfactory explanation of the inflexion of light and the formation of colored fringes, is afforded by that theory which considers light as produced, not by the *emission of luminous particles* from the radiant body, but by the *undulations of a peculiar fluid.* By instituting an analogy between the motions of such a fluid, and those of waves, or those of air in producing sound, when those motions are affected by opposing obstacles, or modified by the passage of the fluid through small orifices, Dr. Young and M. Fresnel, two very distinguished opticians, have explained all the phenomena in question in the most satisfactory manner.†

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* Herschel on Light, Sec. 730.

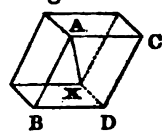
† As we cannot find room to pursue this subject into its details, we must refer the learner, for farther information respecting it, to the writings of Newton, Biot, Brewster and Herschel.

CHAPTER VII.

OF DOUBLE REFRACTION AND POLARIZATION.

937. Double refraction *is a modification which light undergoes in passing through certain media, by which a single pencil of light is divided into two pencils, affording two separate images of the object.*

Fig. 292.



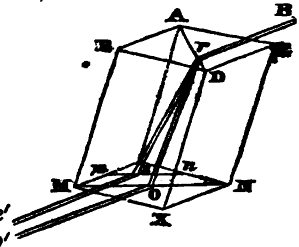
This phenomenon was first observed in a crystal of carbonate of lime denominated *Iceland spar.* This substance may be seen in every cabinet of minerals, presenting the figure of a rhomb. It is a solid bounded by six rhomboidal faces. It is colorless and highly transparent, and distinguished for its beauty in mineralogical collections; but its most remarkable property is that of rendering letters or any other small objects placed behind it *double.*

Though double refraction is exhibited by the Iceland crystal in a manner peculiarly striking, yet this phenomenon is by no means confined to that substance. It takes place in all transparent crystals except those which cleave in planes parallel to the sides of a *cube*, or a regular *octaėdron.* It also occurs in a variety of other bodies which are more or less transparent, where there is any disposition towards a regular arrangement of the particles, such as hair, quills, and the like, and in all bodies when in a state of unequal dilation or compression.

938. The explanation of this singular effect has exercised the sagacity of the profoundest philosophers, at the head of whom are Newton and Huygens. Inquiries respecting it, have of late years been associated with those respecting the Polarization of Light, both of which subjects have been studied with the greatest attention and zeal by some of the first philosophers of the present century; and their investigations have opened a new field of philosophical curiosity, no less ample than fertile. In a work so limited as the present, it will be impossible to give any thing more than a very slight sketch of these subjects, to serve merely for the purposes of an in-

troduction to studies which, in order to be fully understood require to be prosecuted for a length of time proportioned to their extent and intricacy.

Fig. 293.



939. If a rhomb of Iceland spar, represented in Fig. 293, be placed above a black line drawn on white paper, and viewed with the eye at R, the line will appear double, as *mn*, MN, or if we cause a pencil of light R*r* to fall upon the surface of the rhomb, it will be separated into two pencils *r*O, *r*E, each of which will emerge from the rhomb at *o'* and *e'* in the directions O*o'*, E*e'* parallel to R*r*. The pencil R*r* has therefore suffered *double refraction* in passing through the rhomb, and as the same effects will take place by making the pencil R*r* fall at the same incidence, and in the same direction, relative to the summit A upon any point of any of the faces, it is manifest that the double refraction cannot arise from any difference of density in different parts of the rhomb.

940. In order to prove this by direct experiment, let the angles of the ray *r*O, *r*E be measured, corresponding to the different angles of incidence R*r*, beginning at a perpendicular incidence of 0°. It will then be found that at 0° the ray *r*O has suffered no refraction; and that at 10°, 20°, 30°, &c. its refraction is such as it should be by the ordinary law of the sines; the sine of the angle of refraction being to the sine of the angle of incidence in a constant ratio. With the ray *r*E, however, the case is very different; and at 0° its angle of refraction, instead of being 0°, is 6° 12′; and at 10°, 20°, 30°, &c. it is such as not to follow the constant ratio of the sines. Hence it follows, that Iceland spar has a double refraction, separating a pencil of light into two, one of which is refracted according to the ordinary law, and hence called the *ordinary* ray, and the other refracted according to a new or extraordinary law and called the *extraordinary* ray.

941. *In all doubly refracting substances there are one or more* LINES, *or one or more* PLANES, *along which there is no double refraction.* Those substances in which there is only one such line or

plane, are called *crystals with one optic axis;* and those which have two such axes or planes, are denominated *crystals with two optic axes.*

An axis of double refraction, however, is not, like the axis of the earth, a *fixed line* within the rhomb or crystal. It is only a *fixed direction:* for if we divide, as we may do, the rhomb ABC (Fig. 292.) into two or more rhombs, each of these separate rhombs will have its axis of double refraction; but when these rhombs are again put together, their axes will all be parallel to AX. Every line, therefore, within the rhomb parallel to AX, is an axis of double refraction; but as these lines have all one and the same direction in space, the crystal is still said to have only one axis of double refraction.*

In making experiments with different crystals, it is found that in some the extraordinary ray is refracted *towards* the axis AX, while in others it is refracted from the same axis. In the first case, the axis is called a *positive* axis, and in the second case, a *negative* axis of double refraction.†

Fig. 294.

942. In order to give a familiar explanation of the law of double refraction, let us suppose that a rhomb of Iceland spar is turned in a lathe to form a sphere, as shown in Fig. 294, AX being the axis both of the rhomb and the sphere. If we now make a ray pass along the axis AX, after grinding or polishing a small flat surface at A and X,

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* Herschel, in his Treatise on Light, illustrates this subject by the following simile. Suppose a mass of brick-work or masonry, of great magnitude, built of bricks all laid parallel to each other. Its exterior form may be what we please; a cube, a pyramid, or any other figure. We may cut it, (when hardened into a compact mass,) into any shape, a sphere, a cone, a cylinder, &c.; but the edges of the bricks within it, lie still parallel to each other; and their directions, as well as those of the diagonals of their surfaces, or of their solid figures, may all be regarded as so many axes, i. e. lines having (so long as the mass remains at rest) a determinate position, or rather *direction* in space, no way related to the exterior surfaces, or linear boundaries of the mass, which may cut across the edges of the bricks in any angles we please.

† Brewster.

perpendicular to AX, we shall find that there is no double refraction; the ordinary and extraordinary ray forming a single ray, and objects seen behind one of these new surfaces, (the eye being supposed to look perpendicularly through the other surface in the direction of the axis,) appear no longer double but single. Hence,

The index of refraction along the axis AX will be	1.654 for the ordinary ray. 1.654 for the extraordinary ray.
	0.000 difference.

If we do the same at any point, a, about 45° from the axis, we shall have,

The index of refraction along the line RabO, which is nearly perpendicular to the face the rhomb,	1.654 ordinary. 1.572 extraordinary.
	0.082 difference.

If we do the same at any point of the equator CD, inclined 90° to the axis, we shall have,

The index of refraction perpendicular to the axis,	1.654 ordinary. 1.483 extraordinary.
	0.171 difference.

Hence it follows, that the index of extraordinary refraction is the same at all angles with the axis AX; and hence, in every part of a circle described on the surface of the sphere round the pole A or X, the index of extraordinary refraction has the same value, and consequently the double refraction or separation of the rays will be the same. *In crystals, therefore, with one axis of double refraction, the lines of equal double refraction are circles parallel to the equator, or circles of greatest double refraction.*

In *quartz* the index of extraordinary refraction *increases* from the pole A to the equator CD, whereas in the foregoing example of Iceland spar it *diminishes*, and the extraordinary ray appears to be drawn to the axis.

943. A great number of crystals have *two* axes of double refraction, or two directions inclined to each other along which the double refraction is nothing. In crystals with one axis, the axis has the same position, whatever be the color of the pencil of light which is used;

but in crystals with two axes, the axes change their position according to the color of the light employed, so that the inclination of the two axes varies with differently colored rays. In Rochelle salts, the inclination of the axis for *violet* light is about 56°, while for *red* light it is about 76°. Some salts have two axes for one color and only one axis for another.

Until recently it was supposed that the number of optic axes never exceeds two;* but Dr. Brewster has lately discovered an example of a mineral (*analcime*) which has an indefinite number of axes of double refraction, in the direction of which light suffers no separation, although when passing through the body in any other direction it undergoes double refraction.

A cylinder of glass, first heated red hot, and then rolled on a plate of metal until it is cold, acquires a permanent doubly refracting structure. If, instead of heating the glass cylinder, we had placed it in a vessel, and surrounded it with boiling oil or boiling water, it would have acquired the same doubly refracting structure, when the heat had reached the axis; but this structure is only transient, as it disappears when the cylinder is uniformly heated. Analogous structures may be produced by pressure, and by the induration of soft solids, such as animal jellies, isinglass, &c.

944. If the cylinder in the preceding explanation is not a regular one, but has its section perpendicular to the axis every where an *ellipse* instead of a *circle*, it will have two axes of double refraction. In like manner, if we use *rectangular plates* of glass instead of cylinders, in the preceding experiment, we shall have plates with *two planes* of double refraction; a positive structure being on one side of each plane and a negative on the other. If we use perfect *spheres*, there will be axes of double refraction along every diameter, and consequently an infinite number of them. The crystalline lenses of the eyes of almost all animals, whether their figures be those of lenses, spheres, or spheroids, have one or more axes of double refraction.

* See Herschel on Light, Sec. 781.

Polarization of Light.

945. Polarization of Light *is a change which light undergoes after certain refractions or reflexions, by which a ray acquires* polarity, *or different properties on different sides.*

This quality of light, which is one of the most remarkable of all its properties, was discovered by Huygens during his investigations into the cause of double refraction as exhibited in the Iceland Crystal; but the attention of opticians was more particularly directed towards it by the discoveries of Malus in 1810. The knowledge of this singular property of light has afforded an explanation of many of the most intricate phenomena in optics.

946. With respect to the light of the sun, whether it be direct or reflected, whether it be white light or one of the prismatic colors, no such difference of properties exists in the different sides of a ray; and the same is true of the light of a candle or any self-luminous body. But if instead of employing a ray emitted directly from the sun or from any self-luminous source, we subject to examination a ray that has undergone double refraction, or a certain kind of reflexion to be more particularly described hereafter, or that has been in any one of a great variety of ways subjected to the action of material bodies, it seems to have acquired *sides*; a right and a left, a front and a back; and the *intensity*, though not the *direction* of the reflected or transmitted portion depends materially on the position with respect to these sides in which the plane of incidence lies, though every thing else remains precisely the same. It may assist the learner to conceive of the distinction between a common and a polarized ray of light, to liken the former to a cylindrical rod, as a large wire, and the latter to a flat plate of the same diameter. The rod would move through a resisting medium, as water for example, with the same facility whatever side were foremost; but the plate would move with far greater facility in the direction of its narrow than in that of its broad edge. Thus a thin sheet may be slipped between the bars of a grating, which would present an insuperable obstacle to it if applied crosswise.

947. But to be more particular, and to give a more clear conception of the marked distinction which exists between a polarized and an unpolarized ray. There are many crystallized minerals, which when cut into parallel plates are sufficiently transparent, and let pass abundance of light with perfect regularity, but which, nevertheless, at its emergence, is found to have acquired that peculiar modification here in question. One of the most remarkable of these is the *tourmalin*, a mineral which crystalizes in long prisms, the lateral faces of which are often so numerous as to give the specimen almost a cylindrical form. Now if we take one of these crystals and slit it (by the aid of a lapidary's wheel) into plates parallel to the axis of the prism, of moderate and uniform thickness, of about $\frac{1}{20}$ of an inch, and well polished, luminous objects may be seen through them as through plates of colored glass. Let one of these plates be interposed perpendicularly between the eye and a candle. Now holding this first plate in a fixed position, with its axis vertical for instance, let a *second* be interposed between it and the eye, and turned round slowly in its own plane, and a very remarkable phenomena will be seen. The candle will appear and disappear alternately at every quarter revolution of the plate, passing through all gradations of brightness, from a maximum down to a total, or almost total evanescence, and then increasing again by the same degrees as it diminished before. If we now attend to the *position* of the second plate with respect to the first, we shall find that the *maximum* of illumination takes place when the axis of the second plate is parallel to that of the first, so that the two plates have either the same positions with respect to each other, that they had in the original crystal, or positions differing by 180°, while the *minimum*, or evanescence of the image takes place exactly 90° from this parellelism, or when the axes of the two plates are exactly crossed. In tourmalins of a good color, the stoppage of the light in this situation is total and the combined plate, though composed of elements separately very transparent of the same color, is perfectly opake. In others it is only partial; but however the specimen be chosen, a very marked defalcation of light in the crossed position takes place. We shall at present suppose that the specimens employed possess the property in question in its greatest perfection. Now it is evident that the light which has passed through the first plate has acquired in so doing a property

totally distinct from those of the original light of the candle. The latter would have penetrated the second plate equally well in all its positions, while in others it passes through readily; and these positions correspond to certain *sides* which the ray has acquired, and which are parallel and perpendicular respectively to the axis of the first plate. Moreover, when these sides are once acquired, they are retained by the ray in all its future course, (provided it be not again otherwise modified by contact with other bodies) for it matters not how great the distance between the two plates is,—whether they are in contact, or many inches, miles, or yards asunder, since, in all these cases, not the least variation is perceived in the phenomena in question. If the position of the first plate be shifted, the sides of the transmitted ray shift with it, through an equal angle, and the second will no longer extinguish it in the position it at first did, but must be brought into a position removed there-from, by an angle equal to that through which the first plate has been made to revolve.

948. But it is not exclusively by such means that the polarization of light may be effected, nor is this the only character which distinguishes polarized from ordinary light. The following are the principal *means* by which the polarization of light may be performed, viz.

1. By *transmission* through a regularly crystallized medium possessed of the property of *double refraction*.

2. By *reflexion* at a proper angle from the surfaces of transparent media.

3. By transmission through *transparent*, *uncrystallized plates*, in sufficient number and at proper angles.

4. By transmission through various bodies, such as agate, mother-of-pearl, &c. which have an approach to a *laminated structure*, and an *imperfect state of crystallization*.

949. The *characters* which are found invariably to co-exist in a polarized ray, being the chief of those by which it may be most easily recognized as polarized, are—

1. Incapability of being transmitted by a plate of tourmaline, as above described, when incident perpendicularly on it, in certain positions of the plate; and ready transmission in others at right angles to the former.

2. Incapability of being reflected by polished transparent media at certain angles of incidence, and in certain positions of the plane of incidence.

3. Incapability of undergoing division into two equal pencils by double refraction, in positions of the doubly refracting bodies, in which a ray of ordinary light would be so divided.

Besides these, there might be enumerated a vast variety of other characters, which, however, it will be better to regard as *properties* at once of polarized light, and of the various media which effect it. It cannot fail to be remarked, that all these characters are of the *negative* kind, and consist in denying to polarized light, properties which ordinary light possesses, and that they are such as affect the *intensity* of the ray, not its *direction*. Thus the direction which a polarized ray will take under any circumstances of the action of media, is never different from what an unpolarized ray might take, and from what a portion of it actually does take. For instance, when an unpolarized ray is separated by double refraction into two *equal* pencils, a polarized ray will be divided into two *unequal* ones, one of which may even be altogether evanescent, but their directions are precisely the same as those of the pencils into which the unpolarized ray is divided. Hence, we may lay it down as a general principal, that the *direction* taken by a polarized ray, or by the parts into which it may be divided by any reflexions, refractions, or other modifying causes, may always be determined by the same rules as apply to unpolarized light; but the relative *intensities* of these portions differ from those of similar portions of unpolarized light, according to certain laws, which it is the business of the optical inquirer to ascertain.*

950. The first method of polarization is *by double refraction*. When a beam of light suffers double refraction as in the Iceland Spar, where the ray R*r* (Fig. 293.) is incident in the plane of the principal section, or, what is the same thing, in a plane passing through the axis, the two pencils *r*O, *r*E are each polarized; the plane of polarization of the ordinary ray *r*O being in the principal section, or

* Herschel, *Treatise on Light*, Sects. 816—819.

in a vertical line, and the plane of polarization of the extraordinary ray *r*E being at right angles to the principal section, or in a horizontal line.

The phenomena which arise from this opposite polarization of the two pencils may be well seen in Iceland spar. For this purpose let A*r*X be the principal section of a rhomb of Iceland spar, Fig. 295, through the axis AX, and perpendicular to one of the faces, and let A′FX′ be another similar section, all the lines of the one being parallel to all the lines of the other. A ray of light R*r*, incident perpendicularly at *r* will be divided into two pencils; an ordinary one, *r*D, and an extraordinary one, *r*C. The ordinary ray falling on the second crystal at G, again suffers extraordinary refraction, and emerges at K an ordinary ray, O*o*, with its plane of polarization vertical. In like manner the extraordinary ray, *r*C, falling again on the second crystal at F, suffers extraordinary refraction, and emerges at H an extraordinary ray, E*e*, with its plane of polarization horizontal. These results are exactly the same as if the two crystals had formed a single crystal, by being united at their surfaces, CX, A′G, either by natural cohesion, or by a cement. Let the upper crystal AX now remain fixed, with the same ray R*r* falling upon it, and let the second crystal A′X′ be turned round 90°, so that its principal section is perpendicular to that of the upper one, as shown in Fig. 296; then the ray DG ordinarily refracted by the first rhomb will be extraordinarily refracted by the second.

Fig. 295.

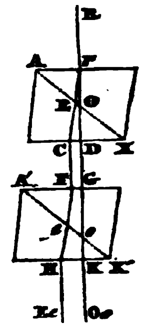
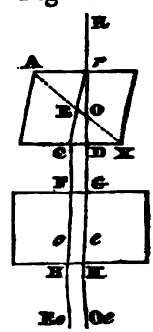


Fig. 296.



The pencils or images formed from the ray R*r*, in the two positions shown in Figs. 295, 296, may be thus described as marked in the Figures.

O is the pencil refracted *ordinarily* by the *first* rhomb.

E is the pencil refracted *extraordinarily* by the *first* rhomb.

o is the pencil refracted *ordinarily* by the *second* rhomb.

e is the pencil refracted *extraordinarily* by the *second* rhomb.

O*o* is the pencil refracted *ordinarily* by both rhombs in Fig. 295.

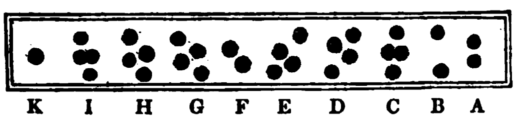
Ee is the pencil refracted *extraordinarily* by both rhombs in Fig. 295.

Oe is the pencil refracted *ordinarily* by the *first*, and *extraordinarily* by the *second* rhomb in Fig. 296.

Eo is the pencil refracted *extraordinarily* by the *first*, and *ordinarily* by the *second* rhomb in Fig. 296.

In both the cases shown in Figs. 295, 296, when the planes of the principal sections of the two rhombs are either parallel as in Fig. 295, or perpendicular to each other, as in Fig. 296, the nearest rhomb is not capable of doubly refracting or dividing into two, any of the pencils which fall upon it; but in every other position between the parallelism and the perpendicularity of the principal sections, the two pencils formed by the first rhomb will be refracted doubly by the second.

Fig. 297.



In order to explain the appearances in all intermediate positions, let us suppose that the ray *Rr* proceeds from a round aperture, like one of the circles at A, Fig. 297, and that the eye is placed behind the two rhombs at HK, Fig. 295, so as to see the images of this aperture. Let the two images shown at A, be the appearance of the aperture at R, seen through one of the rhombs by an eye placed behind CD, Fig. 295, then B will represent the images seen through the two rhombs in the position in Fig. 295, their distance being doubled, from suffering the same quantity of double refraction twice. If we now turn the second rhomb, or that nearest the eye from left to right, two faint images will appear, as at C, between the two bright ones, which will now be a little fainter. By continuing to turn, the four images will be all equally luminous, as at D; they will next appear as at E; and when the second rhomb has moved round 90°, as in Fig. 296, there will be only two images of equal brightness, as at F. Continuing to turn the second rhomb, two faint images will appear, as at G; by a farther rotation they will be all equally bright, as at H; farther on they will become unequal, as at I; and at 180° of revolution, when the planes of the principal section are

again parallel, and the axes AX, A′X′ at right angles nearly to each other, all the images will coalesce into one bright image, as at K, having double the brightness of either of those at A, B, or F, and four times the brightness of any of the four at D and H. If we now follow any one of the images AB, from the position in Fig. 295, where the principal sections are inclined 0° to one another, to the position in Fig. 296, where it disappears at F, we shall find that its brightness diminishes as the square of the cosine of the angle formed by the principal sections, while the brightness of any image from its appearance between B and C Fig. 295, to its greatest brightness at F, increases as the square of the sine of the same angle.

951. By considering the preceding phenomena it will appear that whenever the plane of polarization of a polarized ray, whether ordinary or extraordinary, coincides with or is parallel to the principal section, the ray will be refracted *ordinarily;* and whenever the plane of polarization is perpendicular to the principal section it will be refracted *extraordinarily*. In all intermediate positions it will suffer both kinds of refraction, and will be doubly refracted; the ordinary pencil being the brightest if the plane of polarization is nearer the position of parallelism, than that of perpendicularity, and the extraordinary pencil the brightest if the plane of polarization is nearer the position of perpendicularity than that of parallelism. At equal distances from both these positions, the ordinary and extraordinary images are equally bright.

952. It does not appear from the preceding experiments that the polarization of the two pencils is the effect of any polarizing force resident in the Iceland Spar, or of any change produced upon the light. The Iceland spar has nearly separated the common light into its two elements, according to a different law, in the same manner as a prism separates all the seven colors of the spectrum from the compound white beam, by its power of refracting the elementary colors in different degrees. The re-union of the two oppositely polarized pencils produces common light, in the same manner as the re-union of all the seven colors produces white light.*

* Brewster's *Treatise on Optics*, Ch. XVIII.

CHAPTER VIII.

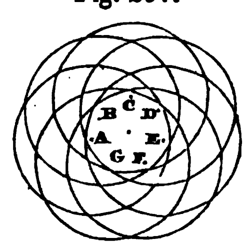
OF VISION.

953. As a preparation for studying the optical structure of the eye, and the laws of vision, it will be useful first to learn in what way images of external objects are formed in a dark room, by light admitted through a hole in the window shutter.

954. *A beam of light from the sun, entering into a dark room through a small orifice and striking upon an opposite wall or screen, forms a circular image on the wall, whatever be the shape of the orifice.*

We will suppose the orifice to be comparatively large, as an inch in diameter, and of a triangular or of an irregular shape; the image formed on the wall will still be circular. For, suppose the orifice to be reduced to a very small circular hole, as a pin hole, (which may easily be done by placing over the orifice a metallic plate, as a sheet of lead, pierced by a pin); then the rays of the sun passing through this small opening would of course be circular. But the large irregular orifice may be considered as made up of such smaller apertures, or the metallic plate may be conceived to be pierced with an indefinite number of pin holes, and the entire image formed upon the wall may be conceived to be made up of an assemblage of all these images of the sun blended with each other, and therefore as bounded by innumerable curve lines composed of the individual circles.

Fig. 297.



If the screen be brought near to the orifice, however, the image will be of the same figure as the orifice; for the rays after they have passed the orifice, must have diverged considerably before the sections that form the image shall afford circles so large, that their blended circumferences shall compose a circular figure. (See Fig. 297.)

If the plane which receives the image, be not parallel to the orifice, then the image will be elliptical, being the section of a cone oblique to its axis.

Circular images of the sun are sometimes projected on the ground, through the small openings among the leaves of trees. During an eclipse of the sun, these images copy the figure of the eclipse.

If there be various orifices near to each other, *three*, for example, through which a beam of the sun shines into a dark room, we shall observe at first, at a certain distance, three distinct luminous circles. At a greater distance, these three circles begin to be blended, and finally, on enlarging sufficiently, they unite to form a single circle.

955. *If, instead of a beam of solar light, we admit into a dark room, through an opening in the shutter, the light reflected from various objects without, an inverted picture of these objects will be formed on the opposite wall.*

A room fitted for exhibiting such a picture is called a *Camera Obscura.*

From what has been before explained, it will be readily understood, that from every point in the object, innumerable rays of light proceed and fall upon the window shutter. Of these, however, none can enter the aperture except such as are very near to each other, all others diverging too far to enter a small opening. It is essential to the *distinctness* of the picture that rays which proceed from every point in the object, should be collected into corresponding points in the image, and should exist there free from any mixture of rays from any other point; and it is essential to the *brightness* of the picture that as many rays as possible should be conveyed from each point in the object to its corresponding point in the image. To render the picture distinct, therefore, the opening in the window shutter must be small, else the pencils of rays from different points will *overlap* each other, and confuse the picture; but as the orifice is diminished the brightness of the picture is impaired, since, in this case, a smaller number of rays is conveyed from the object to the image.

These modifications of the picture according to the size of the aperture, may be easily exhibited by beginning with a circular aperture two or three inches in diameter, and reducing its size gradually

by covering it with a piece of board, or a metallic plate, perforated with holes of different sizes.*

956. *If, instead of passing through the naked orifice, the rays be received on a convex lens, an inch and a half or two inches in diameter fixed in the window shutter, a very bright and distinct picture of the external landscape will be formed on a screen, placed at the focal distance of the lens.*

The image is *brighter* and more *distinct* than when formed without the aid of the lens, first, because the diameter of the lens may be so great as to receive and transmit a much larger portion of the rays which proceed from each point of the object, than would be compatible with distinctness, if so large a naked aperture were employed; secondly, because the rays of each pencil are brought more accurately to a separate focus; and, thirdly, because, the picture being formed nearer to the window shutter, it is smaller, and of course the light, being spread over less space, is more intense.

A convex lens fixed in a ball, is used for this purpose, which is so attached to the opening in the shutter as to be capable of being turned towards different parts of the landscape, like the eye-ball in its socket. Such a lens with its accompanying parts, is called a *Scioptic ball.*

In a bright sunny day, where the sun is on the side of the house opposite to the shutter, and of course illuminating the sides of objects which face the window, we may form either with or without the aid

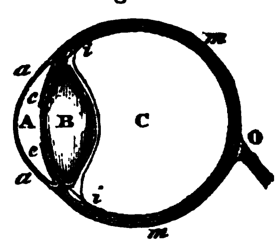
* A small room, ten feet square for example, having a window opening towards an unobstructed landscape, may easily be converted into a camera obscura. The perforation in the shutter, must be made equidistant from the sides of the room; and from the aperture as a center, with a radius equal to the distance of the opposite wall, describe an arc of a circle, upon which as a base a new concave wall is to be constructed, finished with stucco. The other walls and ceiling are to be colored a dead black, while the concave wall, for receiving the image, is made as white as possible. On admitting the light through an aperture half an inch in diameter, a beautiful and distinct picture will be formed on the opposite wall.

of the scioptic ball, a very striking and beautiful picture of external objects, exhibiting each in its relative situation, of a size and brightness corresponding to its distance, with all the colors and the most delicate motions of the landscape. The name *camera obscura*, which appropriately belongs to such a chamber, is also extended to certain boxes in which similar pictures are formed, with peculiar devices for rendering the image erect instead of inverted. The structure of these portable camera obscuras, may be described more particularly among other optical instruments.

The eye is a camera obscura, and the analogy existing between its principal parts, and the contrivances employed to form a picture of external objects as in the preceding experiments, will appear very striking on comparison.

957. The EYE* is an assemblage of lenses which concentrate the rays emanating from each point of external objects on a delicate tissue of nerves, called the *retina*, there forming an image or exact representation of every object, which is the thing immediately perceived or *felt* by the retina. Figure 299 is a section of the human eye through its axis in a horizontal plane. Its figure is, generally speaking, spherical, but in front considerably more prominent than the corresponding portion of a sphere. The eye consists of three principal chambers, filled with media of perfect transparency, whose refractive powers differ considerably among themselves, but none of them is greatly different from pure water. The first of these media, A, occupying the anterior chamber, is called the *Aqueous Humor*, and consists, in fact, chiefly of pure water, holding in solution a little common salt and gelatine, with a trace of albumen. Its refractive index (Art. 884.) is almost precisely that of water, viz. 1.337, that of water being 1.336. The cell in which the aqueous humor is contained, is bounded, on its anterior side, by a strong, horny, and delicately transparent coat, *aa*,

Fig. 299.



* The subjoined description of the eye is taken chiefly from Herschel's Treatise on Light.

and is called the *cornea*, the figure of which is an ellipsoid, produced by the revolution of an ellipse about its major axis.

We have seen (Art. 897,) that convex lenses of a spherical curvature do not bring rays of light accurately to a focus, but spread the light over a space of greater or less extent, which is called the spherical aberration of the lens. It has also appeared (Art. 899,) that if the lens be made of the figure produced by the revolution of an ellipse on its major axis,—an ellipse whose major axis is to the distance between the foci, as the sine of incidence is to the sine of refraction; then the rays will be brought accurately to a focus, and no spherical aberration will take place. We have before us, in the aqueous humor, an example of this construction. Its figure is such an ellipsoid, the ratio of whose major axis to the distance between the foci, is almost precisely the same with that which exists between the sines of the incidence and refraction; the former ratio being expressed by 1.3, the latter by 1.337; hence parallel rays incident on the cornea in the direction of its axis, are made to converge to a focus situated behind the cornea, with almost mathematical precision, the aberration, which would have occurred had the external surface been a spherical figure, being almost completely destroyed.

The posterior surface of the chamber A of the aqueous humor is limited by the *Iris cc*, which is a kind of circular opake screen, or diaphragm consisting of muscular fibres, by whose contraction or expansion, an aperture in its center called the *pupil* is diminished or dilated, according to the intensity of the light. In very strong lights, the opening of the pupil is greatly contracted, so as not to exceed twelve hundredths of an inch in the human eye, while in feebler illuminations it dilates to an opening not exceeding twenty five hundredths or double its former diameter. The use of this is evidently to moderate and equalize the illumination of the image on the retina, which might otherwise injure its sensibility. In animals, as the cat, which see well in the dark, the pupil is almost totally closed in the day time, and reduced to a very narrow line; but in the human eye, the form of the aperture is always circular. The contraction of the pupil is involuntary, and takes place by the effect of the stimulus of the light itself; a beautiful piece of self-adjusting mechanism, the play of which may be easily seen by bringing a candle near to the eye, while directed to its own image in a looking glass. Immediate-

ly behind the opening of the Iris, lies the *Crystalline Lens*, B, enclosed in its capsule, which forms the posterior boundary of the chamber A. The figure of the crystalline lens is a solid of revolution, having its anterior surface much less curved than the posterior. Both surfaces are ellipsoids of revolution about their lesser axes; but the axes of the two surfaces are neither exactly coincident in direction, with each other, nor with that of the cornea. This deviation would be fatal to distinct vision, were the crystalline lens very much denser than the others, or were the whole refraction performed by it. This however is not the case; for the mean refractive index of the lens is only 1.384, while that of the aqueous humor as we have seen, is 1.337; and that of the *vitreous* humor C, which occupies the third chamber, is 1.339; so that the whole amount of bending which the rays undergo at the surface of the crystalline is small in comparison with the inclination of the surface at the point where the bending takes place; and since near the vertex, a material deviation in the direction of the axis can produce but a very minute change in the inclination of the ray to the surface, the cause of error is so weakened in its effect, as probably, to produce no appreciable aberration. The consistence of the crystalline is that of a hard jelly, and it is purer and more transparent than the finest rock crystal.

In the crystalline a very curious and remarkable contrivance is adopted, for overcoming or preventing the spherical aberration which (Art. 897) belongs to lenses of this form, which refract the rays more towards their marginal than near their central parts, and hence do not bring all the rays belonging to one pencil to the same focus. Here the difficulty is obviated by giving to the central portions of the crystalline a proportionately *greater density*, thus increasing its refractive power so as exactly to correspond to that of the other portions of the lens.

The posterior chamber C of the eye is filled with the *Vitreous Humor*, a fluid differing neither in specific gravity nor in chemical composition, in any sensible respect from the aqueous; and as we have already seen (Art. 884,) having a refractive index but little superior to it. Its name is derived from its supposed resemblance to melted glass; it is a clear, gelatinous fluid, very much resembling the white of an egg. Rays of light diverging from various objects without, on passing through the aqueous humor, (which is a concavo-

convex lens) have their divergency much diminished, or even, in most cases are rendered converging, and in this state are transmitted through the crystalline, which has precisely such a degree of refractive power as enables it to bring them to a focus at the distance of the retina, which, as a screen, is spread out to receive the image. The retina as its name imports, is a kind of white net-work, like gauze formed of inconceivably delicate nerves, all branching from one great nerve O, called the *optic nerve*, which enters the eye obliquely at the inner side of the orbit, next the nose. The retina lines the whole of the cavity C up to *ii*, where the capsule of the crystalline commences. Its nerves are in contact with, or immersed in, the *pigmentum nigrum*, a very black velvety matter, which covers the *choroid membrane*, *mm*, and whose office is to absorb and stifle all the light which enters the eye as soon as it has done its office of exciting the retina; thus preventing internal reflexions, and consequent confusion of vision. The whole of these humors and membranes are contained in a thick tough coat, called the *sclerotica*, which unites with the cornea and forms what is called the *white of the eye*.

958. Such in general, is the structure by which *parallel* rays, and those coming from very distant objects are brought to a focus on the retina. But there are *special contrivances*, suited to particular purposes, which are no less evincive of design and skill than the general organization of the eye. Some of the most remarkable of these we proceed to mention. The cornea, by protruding, collects the rays of light that come to the eye laterally, and guides them into the eye, thus enlarging the range of vision. It answers to an appendage to the microscope, which will hereafter be described under the name of *field glass*. The motion of the eye-ball, by means of which the pupil may be turned in different directions, conduces to the same purpose. Hence, notwithstanding the minuteness of the aperture which admits the light (and it must be small, otherwise the image will not be distinct) the eye may take in at once, without moving the head, a horizontal range of 110° and a vertical range of 120°, namely, 50° above, and 70° below a horizontal line.*

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* Brewster.

959. As the radiant approaches the lens, the image recedes from it on the other side; (see Fig. 279;) and in our experiments on the formation of images we are obliged either to change the place of the screen every time the distance of the radiant is altered, or to substitute a new lens, which will either throw back the image as much as the increased distance of the radiant brings it forward, or which brings the image as much nearer as the altered place of the radiant tends to carry it off. How then is the distinctness of the image maintained in the eye, notwithstanding the immense variety in the distances of objects? We can conceive of but two ways in which this can be accomplished: either by lengthening or shortening the diameter of the eye in the direction of its axis, so as to alter the distance of the retina from the cornea and crystalline, or by altering the curvature of the refracting lenses themselves, increasing their convexity for near objects, and lessening it for objects that are more remote. Perhaps both causes may operate, but the effect is believed to be produced chiefly by the latter cause, namely, change of figure in the refracting lenses. On this subject, Sir J. Herschel remarks, that it is the boast of science to have been able to trace so far the refined contrivances of this most admirable organ; not its shame to find something still concealed from its scrutiny; for, however anatomists may differ on points of structure, or physiologists dispute on modes of action, there is that in what we *do* understand of the formation of the eye so similar, and yet so infinitely superior, to a product of human ingenuity,—such thought, such care, such refinement, such advantage taken of the properties of natural agents used as mere instruments, for accomplishing a given end, as force upon us a conviction of deliberate choice and premeditated design, more strongly, perhaps, than any single contrivance to be found, whether in art or nature, and render its study an object of the deepest interest.

960. Writers on comparative anatomy express the highest admiration of the adaptation of the eyes of different animals to the media in which they respectively live, and to the peculiar wants or habits of each. Thus the crystalline lens of the fish is formed with peculiar reference to the refracting properties of water. In the human eye, this lens has a refractive power only a little greater than that of water;

but since the light passes out of a much rarer medium, (air,) such a density is sufficient to bring the rays to a focus; but were the density of the crystalline lens in the eye of the fish no greater than in the human eye, receiving the light from a medium (water) almost as dense as itself, it would be unable to give that change of direction to the rays which would be essential to distinct vision. But provision is made for this exigency by giving to the crystalline lens a much greater density, and of course a higher refracting power, which enables it completely to fulfil its purpose.

Animals which have occasion to see in the dark, as the owl and the cat, have the power of opening or closing the pupil to a much greater extent than man. By this means, they are enabled in the dark, to collect a far greater number of rays of light. But as such an expansion of the pupil would, in broad day light, endanger the safety of eyes of such peculiar delicacy, the iris closes over the aperture and diminishes it with every increase in the intensity of the light, a change which is involuntary on the part of the animal. In animals, as birds, which pounce upon their prey, the pupil of the eye is elongated perpendicularly, while in those that ruminate, as the ox, it is elongated horizontally; being, in each case, exactly adapted to the circumstances of the animal.

961. The images of external objects are of course formed *inverted* on the retina, and may be seen there by dissecting off the posterior coats of the eye of a newly-killed animal, as an ox, and exposing the retina and choroid membrane from behind, like the image on a transparent screen, seen from behind. The appearance is particularly striking and beautiful when the eye is fixed like the scioptic ball, in the window shutter of a dark room. It is this image, and this only, which is *felt* by the nerves of the retina, on which the rays of light act as a stimulus; and the impressions therein produced are thence conveyed along the optic nerve to the sensorium, in a manner which we must rank at present among the profounder mysteries of physiology, but which appear to differ in no respect from that in which the impressions of the other senses are transmitted. Thus, a paralysis of the optic nerve produces, while it lasts, total blindness, though the eye remains open, and the lenses retain their transparency; and some very curious cases of half blindness have been successfully re-

ferred to an affection of one of the nerves without the other.* On the other hand, while the nerves retain their sensibility, the degree of perfection of vision is exactly commensurate to that of the image formed on the retina. In cases of *cataract*, when the crystalline lens loses its transparency, the light is prevented from reaching the retina, or from reaching it in a proper state of regular concentration; being stopped, confused, and scattered, by the opake or semi-opake portions it encounters in its passage. The image, in consequence, is either altogether obliterated, or rendered dim and indistinct. If the opake lens be extracted, the full perception of light returns; but one principal instrument for producing the convergence of the rays being removed, the image, instead of being formed *on* the retina, is formed considerably *behind* it, and the rays being received on it in a state of convergence, before they are brought to a focus, produce no regular picture, and therefore no distinct vision. But if we give to the rays, before they enter the eye, a certain degree of divergence, by the application of a convex lens, so as to render the lenses of the eye capable of finally effecting the exact convergence of the rays upon the retina, distinct vision is the immediate result. This is the reason why persons who have undergone the *operation for the cataract*, (which consists either in totally removing, or in putting out of the way, an opake crystalline,) wear spectacles unusually convex. Such glasses perform the office of an artificial crystalline. An imperfection of vision similar to that produced by the removal of the crystalline, is the ordinary effect of old age, and its remedy is the same. In aged persons, the cornea loses someting of its convexity, or becomes flatter. The refracting power of the eye is by this means diminished, and a perfect image can no longer be formed on the retina, the point to which the converging rays tend being beyond the retina. The deficient power is supplied by a convex lens, in a pair of spectacles, which are so selected and adapted to the eye, as exactly to compensate for the want of refracting power in the eye itself, and thus the rays are brought to a focus at the retina, where alone a distinct image can be formed.

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* *Wollaston*, Phil. Trans. 1824.

962. Short-sighted persons have their eyes too convex, forming the image too soon, or before they reach the retina. Concave glasses counteract this effect. Rare cases have occurred where the cornea was so very prominent as to render it impossible to apply conveniently a lens sufficiently concave to counteract its action. Such cases would be accompanied with immediate blindness, but for that happy boldness, justifiable only by the certainty of our knowledge of the true nature and laws of vision, which in such a case has suggested the opening of the eye and removal of the crystalline lens, though in a perfectly sound state.* Other defects of eye sight, whose cause has been ascertained to depend on mal-conformation of the cornea, or some other part of the eye, have sometimes been remedied by adapting to them glasses of a peculiar construction, possessing optical properties adapted to the particular defects they were required to remedy.

963. As we have two eyes, and a separate image of every external object is formed in each, it may be asked, *why we do not see double?*

When we look at an object we direct towards it the optic axis† of each eye, and see most distinctly that point where this axis produced meets the body. In looking at the same point with both eyes, we incline them so as to make the two axes meet in that point: we therefore see this point *in the same place* with both eyes, and it appears as one, the image being brighter than when seen with one eye. If, by any means, the optic axes be prevented from meeting in the same point, double vision is the consequence. Thus we make surrounding objects appear double by pressing the ball of one eye sidewise with the finger. Those who have one eye distorted by a blow, see double, though they sometimes learn by habit to correct the defect, even while the distortion remains. The sense of touch is subject to a similar distortion: if we lay the middle finger across the fore finger and apply the ends of both fingers to any object, as a small ball, or the end of the nose, the object appears double.

* Herschel on Light, Sec. 350–358.

† The optic axis, is the axis of the crystalline lens, or a line passing through the center of the crystalline perpendicular to both its surfaces.

A similar separation of the optic axes, with a similar result, takes place when we hold a small object, as a pin, in front of the eyes, and then direct them to some distant object: the pin appears double. The same effect is produced, when we look intently at an object near the eye, and attempt at the same time to catch a view of a remote object: the latter appears double.

964. The reason why objects appear erect, while their images on the retina are inverted, has given rise to much discussion. It seems, however, not difficult to comprehend, that objects, and the parts of objects, should appear in the direction in which the rays of light emitted from them come to the eye; and accordingly that those which come from the top and bottom of the object should be referred to those points respectively, just as one sound would be known to proceed from the top and another from the bottom of a high tower, merely by the different sensations which they excited in the ear, although the chain of vibrations from the top should strike the bottom, and those from the bottom the top of the ear. Indeed, this very circumstance might be that which determined the relative positions of the two points; and if these sounds presented to the mind a picture of the tower, they would represent it in its natural erect position.

965. Very minute objects, which cannot be seen by direct vision, may sometimes be rendered visible by looking a little away from them, so that their light strikes the eye obliquely. Thus, astronomers in viewing the smallest stars or satellites with the telescope, have sometimes been able in this manner to catch a glimpse of them, when they could not otherwise be seen. This effect is ascribed to the expansion of its image when seen obliquely, which makes its light act on a greater portion of the retina.

966. *The estimation of the* DISTANCES *and* MAGNITUDES *of objects, is not dependent on optical principles alone, but the information afforded by the eye, is taken in connexion with various circumstances that influence the mind in judging of these particulars.*

In the first place, we judge of the distance of an object by the *inclination of the optic axes*, which is greater for nearer objects and

less for objects more remote. But beyond a certain distance, this method is very indeterminate, since great intervals among remote objects would scarcely affect the inclination of these axes. In the second place, we judge of distance by the *apparent magnitude of known objects;* as when a ship of large size, or a high mountain, appears comparatively small, we refer it to a great distance. We are also frequently deceived in our estimate of distance when we are approaching large objects, as a great city, or a lofty mountain: we fancy they are nearer than they actually are. In the third place, we estimate the distance of objects by the degree of *distinctness of the parts,* or *brightness of the colors.* Thus a smoky mountain is referred to a great distance;* a mountain whose sides are precipitous and bare (especially where the rocks have a new and fresh appearance in consequence of having been quarried for use) appears nearer than the reality; vessels, or steam boats, seen through a mist in the night, have sometimes run foul of each other, being supposed by the pilots to be much farther off, in consequence of the indistinctness of their appearance. In the fourth place, our estimate of distance is affected by the *number of intervening objects.* Hence, distances upon uneven ground do not appear so great as upon a plain; for the valleys, rivers, and other objects that lie low, are many of them lost to the sight. On this principle, the breadth of a river appears less when veiwed from one side than from the center; a ship appears nearer than the truth to one unaccustomed to judge of distances on the water; and the horizontal distance of the sky appears much greater than the vertical distance, whence the aërial vault does not present the appearance of a hollow hemisphere, but of such a hemisphere much flattened in the zenith, and spread out at the horizon.

967. A similar variety of circumstances affects our estimate of the *magnitudes* of bodies seen at different distances. First, the *visual angle,* that is, *the angle subtended by the object at the eye,* determines the size of objects that are near; but it is scarely any guide to the dimensions of remote objects, since all such objects subtend angles

* This appearance exhibits the true color of the atmosphere, becoming visible in consequence of the extent of the stratum, and the dark ground which the mountain affords upon which to view it.

at the eye comparatively very small. Thus, on this principle, a fly within a few inches of the eye would appear larger than a ship of war seen at some distance on the water. A giant, nine feet in height thirty feet off, would appear no larger than a child three feet high seen at the distance of ten feet. But as this result is not conformable to experience, it is evident that we must have means of judging of the magnitude of objects, beside that derived from the visual angle. If the giant were to remove from the distance of ten feet from the eye to that of thirty feet, his image on the retina would be only one third as long as before; but, on the other hand, the distance is trebled, and the sort of combination that takes place in us of the two impressions, the one of magnitude the other of distance, is like the constant product of two quantities, of which one increases in the same ratio as the other diminishes; whence the giant would appear constantly of the same height, at whatever distance from us he was seen.*

968. This corrected result, however, we can make only in cases when we are familiar with the actual size of the body. When not thus familiar, we rely too much on the visual angle, and are thus often greatly deceived. A speck on the window being at the instant, supposed to be an object on a distant eminence, is magnified, in our estimation, into a body of extraordinary size (as a line half an inch long into a may-pole); or distant objects supposed to be very near appear of an exceedingly diminutive size. Secondly, the effect of *contrast* is visible in our estimation of the magnitudes of bodies, a given object appearing much below its ordinary size, when seen by the side of those of very great magnitude. Men quarrying stone at the base of a high mountain sometimes appear at a little distance like pigmies, partly from the effect of contrast, but more perhaps from the impression which the mountain gives us of their being nearer than they actually are. Thirdly, objects seen at an angle considerably above or below us, as a man on the top of a spire, or a river in a deep valley seen from the top of a mountain, appears greatly diminished. In these cases, since there are no intervening objects to aid us in estimating the distance, we estimate it too low, and hence (Art. 966.) the ob-

* Haüy.

ject appears less than the reality. Moreover, being seen *obliquely*, its apparent dimensions are diminished on this account, the apparent diameter being determined by the line into which the object is projected perpendicular to the axis of vision. Hence children judge much less accurately both of distances and of magnitudes than adults; and blind persons suddenly restored to sight, have usually displayed an utter inability to judge of these particulars.

CHAPTER IX.

OF MICROSCOPES.

969. *The Microscope is an optical instrument, designed to aid the eye in the inspection of* MINUTE *objects.**

Telescopes, on the other hand, assist the eye in the examination of *distant* bodies. These two instruments have probably more than any other, extended the boundaries of human thought, and no small part of the labor which has been bestowed upon the science of optics, has had for its ultimate object their improvement and perfection.

With the hope of making the learner well acquainted with the principles of the microscope, we shall begin with those varieties of the instrument which are the most simple in their construction, and successively advance to others of a more complicated structure.

970. The simplest microscope is a double convex lens. This, it is well known, when applied to small objects, as the letters of a book, renders them larger and more distinct. Let us see in what manner these effects are produced. When an object is brought nearer and nearer to the eye, we finally reach a point within which vision begins to grow imperfect. That point is called *the limit of distinct vision.* Its distance from the eye varies a little in different persons, but ave-

* μικρὸς, *small*, σκοπέω, *to see.*

rages (for minute objects) at about *five inches*. If the object be brought nearer than this distance, the rays come to the eye too diverging for the lenses of the eye to bring them to a focus soon enough, that is, so as to make the image fall exactly on the retina. Moreover, the rays which proceed from the extreme parts of the object meet the eye too obliquely to be brought to the same focus with those rays which meet it more directly, and hence contribute only to confuse the picture. We may verify these remarks by bringing gradually towards the eye a printed page with small letters. When the letters are within two or three inches of the eye, they are blended together, and nothing is seen distinctly. If we now make a pin hole through a piece of paper, (black paper is preferable,) and look at the same letters through this, we find them rendered far more distinct than before at nearer distances, and larger than ordinary. Their greater *distinctness* is owing to the exclusion of those oblique rays which, not being brought by the eye to an accurate focus with the central rays, only tend to confuse the picture formed by the latter. As only the central rays of each pencil can enter so small an orifice, the picture is made up, as it were, of the *axes* of all the pencils. The *increased magnitude* of the letters is owing to their being seen nearer than ordinary, and thus under a greater angle, an increase of the visual angle having much influence in our estimate of the magnitude of near objects, though it has but little influence in regard to remote objects. (Art. 967.)

971. A convex lens acts on much the same principles, *only it is* still more effectual. It does not *exclude* the oblique rays, but it diminishes their obliquity so much, as to enable the eye to bring them to a focus at the distance of the retina, and thus makes them contribute to the brightness of the picture. The object is magnified as before, because it is seen nearer, and consequently under a larger angle, which enables minute portions to be distinctly recognized by the eye, which were before invisible, because they did not occupy a sufficient space on the retina. The power of a lens to accomplish these purposes, will obviously depend on its refractive power; and this, (supposing the material of which the lens is made to remain the same) will depend on its increased sphericity, and diminished focal distance. Lenses of the smallest focal distance, therefore, other things being

equal, have the greatest magnifying power, and, therefore, spherules or perfect spheres, have the highest magnifying powers of all. When the radiant is situated in the focus of a lens, the rays go out parallel. (Art. 895.) When thus received by the eye, they are capable of being brought to a focus by it, and of forming a distinct image. Hence, by means of a lens, an object may be seen distinctly when it is exceedingly near to the eye, provided it be situated in the focus of the lens. The magnifying power of a lens, therefore, depends on the ratio between its focal distance and the limit of distinct vision. The latter being five inches, a lens whose focal distance is one inch, by bringing the object five times nearer magnifies its linear dimensions in the same ratio, and its superficial dimensions in the ratio of the square. Thus in the case supposed, an object would appear five times as long and broad, and have twenty five times as great a surface. Lenses have been made capable of affording a distinct image of very minute objects, when their focal distances were only $\frac{1}{60}$ of an inch. In this case, the magnifying power would be $\frac{1}{60} : 5$, which is as 1 to 300, or as 1 to 9000 in surface.

972. When, however, an object is so near to the eye, a very minute space covers the whole field of vision, and it is only the minutest objects, or the smallest parts of a body, that are visible in such microscopes. The extent of parts seen by a microscope is called the *field of view*. A microscope of small focal distance has a proportionally small field of view. Moreover, since, when the object is so near to the lens, the rays of light strike the lens extremely diverging, only the central rays of each pencil can be brought accurately to a focus. The more oblique rays, therefore, must be excluded by covering up all but the central portions of the lens, by which means the brightness of the image is diminished. The part of a lens through which the light is admitted, is called its *aperture*. The aperture of a lens of small focal distance and high magnifying powers, must of necessity be small, and one of the principal difficulties in the use of such microscopes, is the want of sufficient light. Hence microscopes of different focal distances are required for different purposes. Where we wish to view a large object at once, we must use a lens which has a large field of view, and of course but comparatively small magnifying powers. Such are the glasses used by watchma-

kers and other artists. Microscopes which magnify but little, but afford a large field of view, are called *magnifyers*, or *magnifying glasses*. Such are the large lenses employed for viewing pictures. But for inspecting the minute parts of a small insect, we require a much higher power; and, the object being very small, a large field of view is not necessary. The only difficulty to be obviated is the want of light; and this evil is remedied, either by placing the object in the sun, or by condensing upon it a still stronger light, by means of apparatus specially adapted to that purpose, which will be described hereafter.*

973. Among the most distinguished achievements of philosophical artists, in our own times, has been the formation of microscopes out of the hardest precious gems, especially the *diamond* and the *sapphire*. The diamond seems to unite in itself almost every desirable quality for this purpose. It will be recollected that this substance is distinguished for its high refractive powers, its index of refraction being 2.439, while that of crown glass is only 1.530 (Art. 884.); hence a given refracting, and of course magnifying, power may be attained with a lens of less curvature, and consequently (Art. 898.) subject to less *spherical aberration*, than glass lenses of the same power. Indeed, it is estimated that the indistinctness arising from spherical aberration, is in a diamond lens only $\frac{1}{18}$th as great as in a glass lens of equivalent power. The sapphire has analogous properties, as also the garnet; and pure rock crystal (quartz) is much esteemed for refracting lenses; but some of the pellucid gems are unsuitable for this purpose on account of their possessing the property of double refraction. The comparative curvatures and thicknesses of three lenses of the same refracting power, made respectively of diamond, sapphire, and glass, are exhibited in the following diagrams.

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* A convenient pocket microscope is sometimes sold in the shops, consisting of a slide of ivory or horn, two or three inches in length, in which are set three or four lenses of different powers, adapted to various purposes.

Fig. 300.

Glass. Sapphire. Diamond.

Since, however, a diamond lens admits of being made much thinner than a glass lens of the same power, the loss of light by absorption is far less (Art. 850.) and the *brightness* of the image is proportionally augmented.

974. Another distinguished and valuable property of the diamond is that it combines with a high refractive, a *low dispersive power*. By dispersive power it will be observed, is meant the power of separating the different colored rays, that is, of decomposing common light into its prismatic elements. Hence, diamond lenses are naturally nearly *achromatic*, or afford images which are destitute of color. But while these favorable qualities were known to appertain to the diamond, which, taken in connexion with its great transparency and purity of structure, were observed to fit it admirably for microscopes of great magnifying powers, yet the extreme hardness of the substance, seemed to render the difficulty of grinding it into the requisite shape almost insuperable. This difficulty has, however, within a few years, been completely overcome by Mr. Pritchard, an eminent English artist, who has constructed a number of diamond and sapphire microscopes, whose performances have equalled the most sanguine expectations.

The following table exhibits the different magnifying powers of Pritchard's sapphire lenses, corresponding to different focal distances.

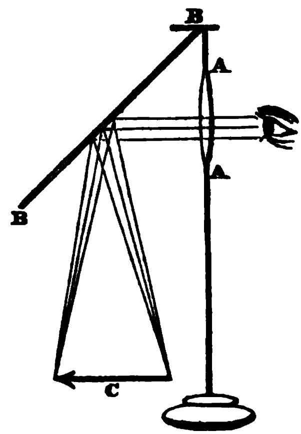
Parts of an inch.	Magnifying Power.	
	Linear.	Superficial.
$\frac{1}{10}$	100	10,000
$\frac{1}{15}$	150	22,500
$\frac{1}{20}$	200	40,000
$\frac{1}{30}$	300	90,000
$\frac{1}{40}$	400	160,000
$\frac{1}{50}$	500	250,000
$\frac{1}{60}$	600	360,000
$\frac{1}{70}$	700	490,000
$\frac{1}{100}$	1000	1,000,000

975. A drop of a transparent liquor may be easily converted into a magnifier, constituting a *Fluid Microscope*. The simplest kind of fluid microscope is formed by drilling a small hole in a plate of brass or lead, and applying to it a drop of water from the point of a pin. If the plate be hollowed out on both sides around the aperture, the water will spontaneously assume the shape of a convex lens. Water, however, possessing only a comparatively low refracting power, (Art. 884.) is less adapted to this purpose than several other fluids, particularly certain transparent balsams and aromatic oils. Sulphuric acid and castor oil answer well, but turpentine varnish and canada balsam are preferred, especially because as they dry they become indurated, and form permanent microscopes. Instead of the aperture in a metallic plate above described, a small plate of glass may be employed, in which case it is only necessary to drop the varnish or balsam on the surface of the plate; and it will assume the figure of a plano-convex lens. The power of the microscope may be varied by employing a larger or a smaller drop, or by suffering it to spread itself on the upper or on the under surface, since the curvature of the drop, and of course its focal distance, is modified by each of these circumstances.

976. The Perspective Glass, which is used for viewing pictures, affords another example of the application of the simple microscope. It consists of a large double convex lens fixed in a frame in a vertical position, from the top of which, on the back side, proceeds a plane mirror which is fixed at an angle of 45° with the horizon, and of course it makes the same angle with the lens. Pictures to be viewed are placed in an inverted position (that is, with the top towards the spectator,) on a table at the foot of the instrument. The mirror, being set at angle of 45° with the horizon, renders horizontal objects erect. (Art. 866.) Its office, therefore, is merely to give a proper *direction* to the rays of light from the picture as they enter the lens, causing them, in fact, to come to the lens in the same manner, as they would do were the mirror removed and the picture set up in a vertical position, parallel to the lens, at a distance from the lens equal to the length of any ray, measured from the picture to the mirror and from the mirror to the lens. (Art. 865.) Again, in order that the image may be erect, it is necessary that the picture

should be placed with its top towards the observer; for since the image of every point in the picture is just as far behind the mirror as the point is before it, those parts of the picture which are designed to occupy the highest parts of the image must be farthest below the mirror. This will be understood from the following diagram.

Fig. 301.



AA, a convex lens fixed vertically in a frame.

BB, a plane mirror making with the horizon an angle of 45°.

C, an object placed horizontally upon the table, the upper part being towards the observer.

The object will be reflected by the mirror into a perpendicular position, and its rays will, therefore, fall on the lens in the same manner as they would were it actually situated perpendicularly, and no mirror were employed. Consequently, if the distance of C from the lens be equal to the focal distance of the lens, the rays will come to the eye parallel, and a distinct and magnified image will be formed. If the distance be greater than the focus (as it may be rendered by depressing C to a lower level) then the rays will come to the eye converging, and the image will be more magnified but less distinct. If the distance of C be less than the focus, the image will be less magnified, but it will be distinct within certain limits. The reasons of these several modifications, will be evident by reflecting on principles already expounded.

When the glass is of good quality, and the picture executed agreeably to the rules of perspective, the various parts are exhibited in their natural positions, and at their relative distances, so as greatly to improve the view. The greater distinctness of the parts and more natural distribution of light and shade than what attends the naked view, is owing not only to the increased magnitude and to the greater quantity of the light emitted from the picture which is collected by the lens and conveyed to the eye, but also to the separation of this portion of light from that which proceeds from various other ob-

jects. The lens both conveys more of the light of the picture to the eye than would otherwise reach it, and it conveys it unmingled with extraneous light. The importance of the latter circumstance is manifested even by looking at the picture through an open tube, through the hand so curved as to form a tube.

977. The microscopes hitherto examined are such as are designed to be interposed between the eye and the object to be viewed, the latter being placed in the focus of parallel rays of the lens, or a little nearer to the lens than that focus, so that the rays of the same pencil may come to the eye either parallel or with so small a degree of divergency, that the lenses of the eye shall be competent to make them converge and form an image on the retina. In this case, as the rays come to the eye in the same manner as rays from larger objects, at a greater distance, seen without the aid of a lens, the position of the object is not changed, that is, it is seen erect. Single microscopes, however, are also employed to form a magnified image on a wall or screen, which is seen by the eye instead of the object itself. Two celebrated instruments, the Magic Lantern and the Solar Microscope, magnify their objects in this manner, in the construction of which the principles under review are happily exemplified.

978. From what has been already learned respecting lenses, the following points will be readily comprehended, being for the most part a recapitulation of principles already explained and demonstrated.

If, in a dark room, we place before a convex lens any luminous object, as a candle, we shall observe the following phenomena. (See Art 895.)

1. If the radiant be placed nearer to the lens than its focus, since the rays will go out diverging, no image will be formed on the other side of the lens.

2. Even when the radiant is in the focus, so that the rays go out parallel, they never meet in a focus, and of course never form an image.*

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* It will be remarked, that when the single microscope is used as an eye glass, the eye itself brings the parallel rays to a focus and forms the image.

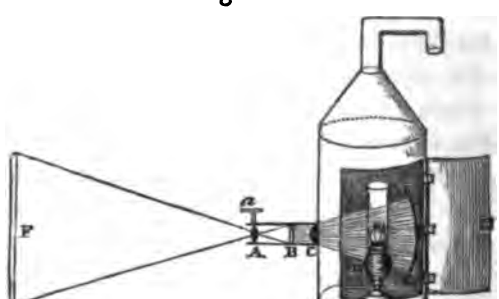
3. But when the radiant is farther from the lens than its focus, the rays converge on the other side, those of each pencil, proceeding from the same point in the object, being accurately united in one point in the image, and occupying that point alone, without the interference of rays from any other point.

4. The axes of the rays from the extreme parts of the object cross each other in the center of the lens. Hence they form an image *inverted* with respect to the object; and, although the rays which make up any individual pencil are made to *converge* by the lens, yet the axes (which determine the magnitude of the picture) diverge from each other after crossing at the center of the lens, and hence the image is greater in proportion as it is formed at a greater distance from the lens. When the object is only a little farther off from the lens than its focus, the image is thrown to a great distance, and is proportionally magnified. As the object is separated farther from the lens (which may be effected either by withdrawing the object from the lens or the lens from the object) the image is formed at a less distance, and is of a diameter proportionally less. (See Art. 896.) Suppose now that we employ a magnifier of so small focal distance, that when the object is placed within one tenth of an inch of the lens, the image is formed on the other side upon a screen or wall at the distance of twenty feet; the object will be magnified in the ratio of $\frac{1}{10}$ to $(20\times12=)$ 240; that is, the image will be 2,400 times greater than the object in diameter, and 5,760,000 times greater in surface. It would seem, therefore, as if nothing more were necessary in order to form magnified images of objects than a dark room, a convex lens, and a screen or wall for the reception of the picture. It must be remarked, however, that when the light which proceeds from the object is diffused over so great a space, its intensity must be greatly diminished, so as to be either incapable of affording a picture which shall be visible at all, or at least sufficiently bright for the purposes of distinct vision. This difficulty is remedied by *illuminating the object;* and it is for this purpose, that most of the contrivances employed in the magic lantern and solar microscope are designed.

979. The MAGIC LANTERN consists of a large tin canister either cylindrical or cubical in its figure, having an opening near the bottom into which air may enter freely to supply the lamp, and a chimney

proceeding from the top and bent over so as to prevent the light of the lamp from shining into the room. The lantern has a door in the side which shuts close, the object being throughout to prevent any light from escaping into the room except what attends the picture. The room itself is made as dark as possible; or, what is better, the experiments are performed by night. In front of the lantern is fixed a large tube, at the open end of which is placed the magnifying lens. In the same tube, at a distance from the lens somewhat greater than the focal distance, the object is introduced, which is usually some figure painted on glass in transparent colors, the other parts of the glass being blackened so that no light can pass through except that which falls on the object and illuminates it, by which means we shall have a luminous image projected on a black ground. For illuminating the object, an argand lamp is placed near the center of the lantern, the light of which is concentrated upon the object in two ways; first, by means of a thick lens, usually plano-convex, so situated between the lamp and the object that the rays which diverge from the lamp shall be collected and condensed upon the object; and, secondly, by means of a concave reflector situated behind the lamp, which serves a similar purpose.

Fig. 302.



A, the magnifying lens.

B, the object, introduced through an opening in the tube.

C, the condensing lens.

D, the lamp.

E, the concave mirror.

F, the image thrown on a screen, or a white wall, in a dark room.

a, a thumb-piece, by which the magnifier may be made to approach or to recede from the object, and thus the image be thrown to a greater or less distance, according to the magnitude required. As the image is inverted with respect to the object, it is only necessary to introduce the object itself in an inverted position, and the image will be erect.

The objects employed in the Magic Lantern are very various, consisting of figures of men and animals; of caricatures; of representations of the passions; of landscapes; and of astronomical diagrams. When the last are employed, this apparatus becomes subservient to a useful purpose in teaching astronomy, and is frequently so employed by popular lecturers on that subject.

980. The SOLAR MICROSCOPE does not differ in principle from the Magic Lantern, only the object is illuminated by the concentrated light of the *sun* instead of that of a lamp. And since a powerful illumination may thus be effected upon minute objects placed before a magnifier of great power, the solar microscope is usually employed to form very enlarged images of the most minute substances, as the smallest insects, the most delicate parts of plants, and other attenuated objects of natural history. For magnifiers, several of different focal distances are employed, varying from an inch to the $\frac{1}{10}$ or $\frac{1}{20}$ of an inch, it being understood that those of the shortest focus and greatest magnifying powers can be used only for the minutest objects, since, when bodies of a larger size are brought so near a small lens, their light strikes the lens too obliquely to be transmitted through it. The magnifying lens is fixed into the mouth of a tube and the object placed near its focus, much in the same manner as in the magic lantern; but instead of the body of the lantern (which contains the illuminating apparatus) a mirror, about three or four inches wide, and from twelve to eighteen inches long, is attached to the other end of the tube. This mirror is thrust through an opening in the window shutter of a dark room, and the mouth of the tube to which it is fixed is secured firmly to the shutter, so that the mirror is on the outside, and the tube with its lenses is on the inside of the shutter. By means of adjusting screws, the mirror is turned in such a way as to direct the sun's rays into the tube, where they are received by one or more of the lenses, called *condensers*, which col-

lect them and concentrate them upon the object, which thus becomes highly illuminated, and capable of affording an image sufficiently bright and distinct, though magnified many thousands or even millions of times. It will be observed that the magnitude of the image depends here, as in other cases of the simple microscope, upon the ratio between the distances of the object and the image from the center of the magnifier. If, for example, the object be within the tenth of an inch of the lens, and the image be thirty feet, or three hundred and sixty inches from it, then the image will be $360 \times 10 = 3600$ times as large as the object in diameter, and $(3600)^2 = 12,960,000$ times in surface. With a given lens, the size of the image depends wholly on the distance to which it is thrown; that is, on the distance of the wall or screen where it is formed.

981. When the solar microscope is well constructed, it affords the most wonderful results, and greatly enlarges our conceptions of the delicacy, perfection, and subtilty of the works of nature. In inspecting *vegetables*, the eye is delighted with the regularity and beauty which characterizes the texture and intricate structure of plants and flowers. The most delicate fibres of a leaf, the pores through which the vegetable fluids circulate, the downy covering of plants, and foliage, as of certain mosses, which is too minute to disclose its figure to the naked eye,—objects of this kind, when expanded under the solar microscope, astonish and delight us by the symmetry of their structure. Their appropriate *colors* are not so well exhibited by this instrument, as by some other forms of the microscope to be described hereafter. In the *animal* kingdom, the solar microscope extends the range of vision in a manner no less surprising and instructive. The minutest insects we are acquainted with, are exhibited to us as animals of the largest size, and often of monstrous shapes, from the multiplicity of their parts and apparent disproportion; and animalcules, or those members of the animal creation which are too minute to be seen at all by the naked eye, are suddenly brought into life in countless numbers. The forms, the motions, and the habits of these beings, are among the most curious revelations of the solar microscope. The *circulation of the blood* may be seen in the fins of fishes and other transparent parts of animals, presenting a very curious and interesting spectacle. The *crystallization of salts*, which

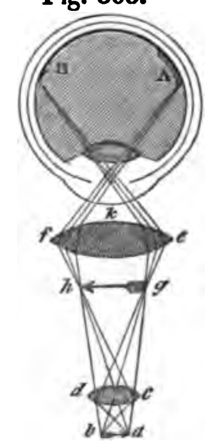
may be exhibited while the crystals are forming and arranging themselves, (as many of them do with great precision and symmetry,) is among the finest representations of this instrument.

Since the light is transmitted through the object, it will of course be understood, that only such objects as are *transparent* can be employed in the manner already described. In some varieties of the solar microscope, there are special contrivances for exhibiting *opake* objects by means of reflected light.

982. If we form an image of an object with the single microscope, (as is done in the magic lantern and solar microscope,) if that image is not too large, we may obviously apply to it a magnifier as we would to an original object of the same size. This is the principle of the Compound Microscope.

The Compound Microscope consists of at least two convex lenses, one of which, called the *object-glass*, is used to form an enlarged image of the object, and the other, called the *eye-glass*, is used to magnify the image still farther.

Fig. 303.



Thus, let *ab* (Fig. 303.) be the object, being placed a little farther from the object glass, *cd*, than the principal focus, the rays of light emanating from it will be collected on the other side of the lens and form an image, *gh*, whose diameter is as much larger than that of the object as its distance from the lens is greater. (Art. 896.) Let *ef* be the eye-glass, which must be placed at such a distance from the image, that the latter shall be in the focus of parallel rays; then the rays proceeding from the image will go out parallel,* and come to the eye, situated behind the glass, in a state favorable for distinct vision.

* It is to be remarked here and in all similar cases, that it is only the rays of *each individual pencil* that are parallel; that is, those rays which come from the same point in the object. The rays of different pencils may cross each other variously, and the different pencils may converge or diverge among themselves; still if the rays of each pencil be parallel to one another, the vision will be distinct.

983. The *magnifying* power of the Compound Microscope is estimated as follows. First, the diameter of the image will be to that of the object as their respective distances from the lens. Secondly, the image is magnified by the eye-glass according to the principles of the single microscope, (Art. 971.) namely, from the ratio of its focal distance to the limit of distinct vision. Thus, suppose the image is formed at ten times the distance of the object; it will of course be magnified ten times. Again, suppose the eye-glass has a focal distance of one inch, the limit of distinct vision being five inches; the image will be farther magnified five times; by both glasses, therefore, the object will be magnified fifty times. If the first ratio be that of one to one hundred, then the instrument will magnify the linear dimensions five hundred times, and the surface two thousand five hundred times. From this double magnifying process, it might be supposed that, by means of the compound microscope, it would be easy to attain a much higher magnifying power than by the single microscope; but this is not the fact, for, in the first place, we cannot form an image of a size beyond certain moderate limits, without making it too large for the eye-glass to cover; or, if an eye-glass of very large field of view be employed, its focal distance must be great, and consequently its magnifying power small. We are, therefore, unable to employ so high a magnifier for our object-glass as we may apply to the naked eye, and we can employ only a microscope of still inferior power for our eye-glass.

984. On account of the necessity of using a large eye-glass to view the magnified image, compound microscopes require to have the tube which contains the glasses, larger towards the eye-glass than towards the object-glass. Sometimes the magnifiers are contained in a box of pyramidal shape, the reason of which is obvious. Of the latter figure is the *Lucernal Microscope*, a variety of the compound microscope which admits of being used with the light of a *lamp* instead of day light, and is furnished with a reflector and a condensing lens by one or the other of which the light of the lamp may be concentrated upon the object. The lucernal microscope is furnished with a piece of ground glass, upon which the image may be received as upon a screen. The object being illuminated by a lamp, and the image being seen in a dark room, this arrangement is very

convenient for drawing insects, flowers, &c. Although the compound does not possess higher magnifying powers than the simple microscope, yet it commands a much greater field of view. We view the image with the eye-glass in the same manner as we view the object with a single microscope; but having already a magnified representation of the object, we have no occasion to apply to the eye so high a magnifier, and therefore we may employ one of greater focal distance which consequently takes in a greater field of view. The field of view is still farther improved in some compound microscopes by interposing a *field glass*, which is a convex lens introduced between the object-glass and the place of the image, and near the latter (as a little below *gh*, Fig. 303,) the effect of which is to diminish the divergency of the pencils of rays, and thus to bring into the range of the eye-glass those pencils, which would otherwise diverge too much to fall within it. It has been before remarked that the cornea performs a similar office for the crystalline lens of the eye. (Art. 958.)

985. Instead of employing a convex lens for the purpose of forming an image of the object, we may use a concave mirror for the same purpose. On this principle are constructed Reflecting Microscopes. The object being placed before the mirror at a distance a little greater than the focal distance, a magnified image will be formed on the other side of the center, as in Fig. 264. To this image we may obviously apply an eye-glass in the same manner as in the common compound microscope. Reflecting microscopes are supposed to have some advantages over the refracting, but they have not come into general use. By making the concave reflector of an parabolic figure, spherical aberration is prevented, (Art. 861.) and reflectors are not liable, like lenses, to form colored images in consequence of the decomposition of the light into its prismatic rays, called *chromatic aberration*. These difficulties, however, when they occur admit of being obviated by peculiar contrivances, which will be more particularly described in connexion with telescopes.

986. Dr. Brewster gives the following *rules* for making microscopic observations.

1. The eye should be protected from all extraneous light, and should not receive any of the light which proceeds from the illuminating center, excepting what is transmitted through, or is reflected from the object.

2. Delicate observations should not be made when the fluid which lubricates the cornea is in a viscid state.

3. The best position for microscopical observations, is when the observer is lying horizontally on his back. This arises from the perfect stability of his head, and from the equality of the lubricating film of fluid which covers the cornea. The worst of all positions is that in which we look downwards vertically.

4. If we stand straight up and look horizontally, parallel markings or lines will be seen most perfectly when their direction is vertical; viz. the direction in which the lubricating fluid descends over the cornea.

5. Every part of the object should be excluded, except that which is under immediate observation.

6. The light which illuminates the object should have a very small diameter. In the day time, it should be a single hole in the window shutter of a darkened room, and at night an aperture placed before an argand lamp.

7. In all cases, particularly when high powers are used, the natural diameter of the illuminating light should be diminished, and its intensity increased, by optical contrivances.*

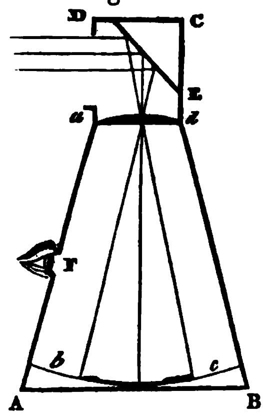
987. The microscope is sometimes employed to form images for the purposes of drawing. In this manner landscapes are represented, objects of natural history are delineated, and artificial pictures are reduced and copied. The two instruments particularly employed for this purpose are the Portable Camera Obscura and the Camera Lucida.

988. The PORTABLE CAMERA OBSCURA, which is used chiefly for delineating landscapes, consists of a wooden box, (answering to the dark chamber, Art. 955.) with which is connected a convex lens

* Brewster's Optics, 345.

so exposed to the landscape as to receive the rays of light from the various objects in it, and form a picture of them on a screen placed within the box at the focal distance of the lens. Such is a general description of the instrument, of which there are several different forms. The following diagram represents a common convenient form.

Fig. 304.



ABCD, a box usually made of thin pieces of mahogany.

a d, a plano-convex lens, this form being preferred because it has less aberration than a double convex. (Art. 898.)

ED, a plane mirror, turning on a hinge at D, and capable of being raised or lowered, so as to admit more or less of the landscape.

b c, a piece of pasteboard, covered with a sheet of fine white paper and bent so as to form a concave screen, and placed at the focal distance of the lens. A casting of stucco, of the figure of a concave portion of a sphere, affords the most perfect picture.

The rays of light from external objects, falling upon the mirror ED are conveyed to the lens in the same manner, as though they came directly from objects at the same distance behind the mirror. Passing through the lens, they are brought to a focus and form a picture of the landscape on the screen, which may be viewed by an opening in the side of the box at F, and may be copied by a hand introduced into the box by an opening below.

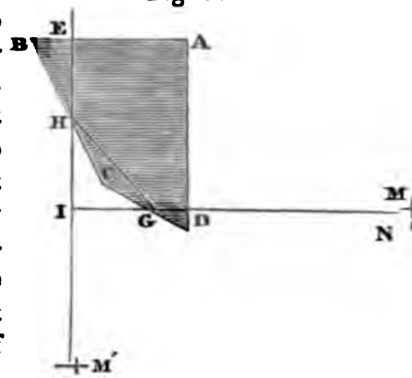
Although the image is inverted with respect to the objects, yet as the spectator, in looking into the box, stands with his back to the landscape, the picture appears erect.

989. The Camera Lucida is an instrument of more recent origin, having been invented by the late Dr. Wollaston. It consists of a prism so contrived that its surfaces, by their reflecting properties,*

* It will be observed in the following illustration, that the rays of light strike the surfaces of the prism at such an angle as to undergo *total reflexion*. (Art. 883.)

give the proper direction to the rays of light, and finally project an image of the object in a convenient position for copying, as is represented in the following diagram.

Fig. 305.



ABCD is a glass prism, having the angle at A 90°, the angle at D 67½°, the angle at C 135°. In taking an observation, the prism is set with the side AD parallel to the object M. A ray of light ND falling perpendicularly upon AD suffers no refraction, but proceeds on to the second surface DC, where it makes with DC, an angle of 22½°, (the complement of the angle at D.) Of course the angle CGH is 22½°, and these two angles, subtracted from 180°, leave NGH=135°. Again, since GCH=135°, and CGH=22½°, therefore CHG and BHE each equal 22½°, and therefore GHE=135°. Produce NG till it meets HM′ in I; then the angles IGH and IHG will be severally 45°, and consequently HIG (which is the angle made by the incident and emergent rays) will be 90°. Therefore, the perpendicular object MN will appear to the eye on a horizontal plane at M′, as far behind the reflecting surface as M is before it. (Art. 865.) Now if the prism is so formed, that the emergent rays shall be very near the angular point B, the eye may take in at once the image and the paper on which it is projected, seeing the former through the prism and the latter by direct vision; and thus the image may be very perfectly sketched. This beautiful instrument is usually mounted in a case, and has various appendages which severally contribute to its utility, but we aim only to convey an idea of its *principle*.*

* For a more extended description of the Camera Lucida, see Nicholson's Phil. Journal, and Tilloch's Phil. Magazine, for 1807.

CHAPTER X.

OF TELESCOPES.

990. *The Telescope is an optical instrument, designed to aid the eye in viewing distant objects.**

The construction of this noblest of instruments, in its different forms, involves the application of all the leading principles of the science of Optics. The study of the Telescope is therefore the study of the science, and a distinct enunciation of the principles involved in it, will serve as a recapitulation of the most useful principles of Optics. The advantage which the student will derive from reviewing these points, as exemplified in their application, will justify us in bringing up distinctly to view various principles already unfolded.

991. The leading principle of the Telescope may be thus enunciated:

By means of either a convex lens, or a concave mirror, an image of the object is formed, which is viewed and magnified with a microscope.

The most general division of the instrument is into Refracting and Reflecting Telescopes; of which the former produce their image by means of a convex lens, and the latter by means of a concave mirror. The instrument, according to the uses to which it is applied, receives the farther denominations of the Astronomical and the Terrestrial Telescope; and also Telescopes are named, after their several inventors, Galileo's, Newton's, Gregory's, Herschel's, &c.

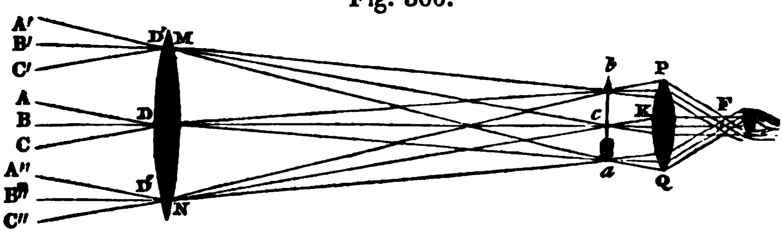
The Astronomical Telescope.

992. We begin with this variety because it is one of the most simple, and because in connexion with it, we may conveniently study the theory of the instrument at large.

* τῆλε, *at a distance*, σκοπέω, *to see.*

The Astronomical Telescope has essentially but two glasses: these are usually fixed in a tube of brass, one at one end, and the other at the other end. The glass at the end of the tube which is directed to the object, is called the *object glass*, and that at the end to which the eye is applied, is called the *eye glass*. The object glass is a convex lens which forms an image of a distant object, as a star, in its focus of parallel rays, and the eye-glass is a microscope with which we view the image, at a distance equal to its focus of parallel rays. Of course, the distance of the two glasses from each other is equal to the sum of their focal distances. See the annexed figure.

Fig. 306.



MN, object glass.

PQ, eye glass.

A′D′, AD, A″D″, parallel rays from the top of the object.

B′D′, BD, B″D″, " " " center ditto.

C′D′, CD, C″D″, " " " bottom ditto.

ba, inverted image formed in the focus of parallel rays.

*b*PF, a pencil of rays, proceeding from the top of the object to the eye glass and rendered parallel.

*c*KF, a similar pencil from the center.

*a*QF, ditto the bottom.

F, point where the different pencils cross the axis.

993. In this instrument we observe a striking resemblance to the Compound Microscope. (Fig. 303.) In the microscope, however, since the object is nearer than the image, the image is greater than the object; but in the telescope, since the object is removed to a great distance, the image is formed much nearer to the lens than the object, and is proportionally smaller. Hence, Compound Microscopes have their tubes enlarged in diameter towards the eye glass, while telescopes have their tubes diminished in that direction. Since

the vertical angles at D, subtended on the one side by the object, and on the other by the image, are equal, were the eye situated at the center of the object glass, it would see the object and the image under the same visual angle, and consequently, both would appear of the same magnitude. Moreover, were the eye placed at the same distance from the image on the other side of it, it would be apparently of the same size as before and therefore of the same apparent diameter as the object. But by means of a microscope, such as the eye glass in fact is, we may view it at a much nearer distance, and of course magnify it to any extent, as was fully shown in explaining the principles of the simple microscope. (Art. 971.) Hence the magnifying power of the telescope depends on the ratio between the focal distances of the object glass and the eye glass. If, as in the figure, the common focus is ten times nearer the eye glass than the object glass, the instrument will magnify ten times; if one hundred times nearer, one hundred times; and so in all other cases. Hence we may increase the magnifying power of the instrument, either by employing an object glass of very small curvature, which throws its image to a great distance, or an eye glass of high curvature and small focal distance. Suppose, for example, the object glass has a focal distance of forty feet, or four hundred and eighty inches, and the eye glass has a focal distance of one tenth of an inch, then the magnifying power of this instrument would be four thousand and eight hundred in diameter, and the square of this number in surface.

994. As the sphericity of the eye glass may be increased indefinitely, and its focal distance diminished to the same extent, it would seem possible to apply very high magnifying powers in very short telescopes. For example, suppose the focal distance of the object glass is twenty four inches; by using a microscope of $\frac{1}{10}$ of an inch focus, we have a power of two hundred and forty. But it must be kept in mind, that such microscopes command only an exceedingly small field of view, and would, therefore, not enable us to see any thing more than a minute portion of an object of any considerable size; and not sufficient light would be transmitted through such an aperture to answer the purpose of vision.—Since the image is inverted with respect to the object, and is viewed in this situation by the eye

glass, objects seen through Astronomical Telescopes appear inverted. By the addition of several more lenses, they may be made to appear erect, as will be shown in the description of the Day Glass, or Terrestrial Telescope; but at every new refraction a certain portion of light is extinguished, a loss which it is important to avoid in instruments designed to be used at night; while, in regard to celestial objects, it is not essential whether they are seen erect or inverted.

The place for the eye to view the image with the best advantage is at F, where the pencils of parallel rays meet.

995. The *difficulties* to be overcome in the construction of a perfect Refracting Telescope, (some of which are very formidable) are chiefly the following: 1. Spherical aberration; 2. Chromatic aberration; 3. Want of sufficient light; 4. Want of a field of view sufficiently ample; 5. Imperfections of glass. Each of these particulars we will briefly consider.

996. *Spherical aberration*, it will be recollected, occasions indistinctness in images formed by lenses, in consequence of the different rays of the same pencil not being all brought to a focus at the same point, those which fall upon the extreme parts of the lens being more refracted and coming to a focus sooner than those which are nearer to the axis. (See Art. 897.) The amount of this error is found to depend on two circumstances, namely, the diameter of the lens, or what is technically called its *aperture*,* and its focal distance, increasing rapidly as the aperture is increased, and diminishing as the focal distance is increased.† *Small apertures and flat or thin lenses are, therefore, most free from spherical aberration.* But if we use small apertures we cannot have a strong light, which is a circum-

* The aperture, strictly speaking, is the diameter of that part of the lens through which, in a given case, light is admitted, whether it be the whole surface or only a part of it.

† It is found by opticians, that the *longitudinal aberration* of lenses, increases as the square of the aperture, with a given curvature, and is inversely as the focal distance, with a given aperture, and that the *lateral aberration* increases as the cube of the aperture, with a given radius, or inversely as the square of the radius with a given aperture.

stance of the greatest importance in astronomical observations, since it is of little consequence to enlarge the dimensions of an object if we have not light enough to render it visible. Indeed, many astronomical objects, as small stars, are rendered visible by the telescope not in consequence of any apparent increase of size, but because this instrument collects and conveys to the eye a much larger beam of light from them than would otherwise enter it. While the diameter of the beam which falls upon the naked eye is only the fraction of an inch, that collected by the telescope may be several inches, or even several feet, according to the size of the instrument. Hence the advantages of large apertures is obvious. Again, we cannot wholly remedy the error in question, though we may diminish it by using very flat lenses which have great focal distances; but the tendency of this expedient is to render the instrument inconveniently long. Other expedients, therefore, become necessary for correcting spherical aberration in refracting telescopes.

997. In the eye glasses, which are liable to the same difficulty, where the lens has a great curvature, as is the case with such as have high magnifying powers, the aperture is necessarily reduced very much, by excluding all the light except what passes through the central parts of the lens. At least this is the case where glass lenses are used. But the microscopes made of diamond, sapphire, and other gems, have not only high refractive powers, but are less subject to spherical aberration than similar lenses of glass. Art. 973. Thus, if three lenses were ground in the same tool, one of plate glass, one of sapphire, and the other of diamond, their respective magnifying powers and aberrations would be as follows:*

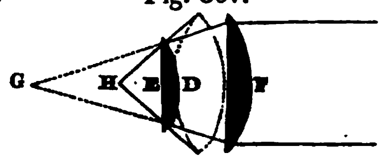
	Magnifying power.	Longitudinal aberration.
Glass,	150	1.167
Sapphire,	250	1.005
Diamond,	400	0.950

This difference in aberration will be much greater if the lenses be so formed as to give the same magnifying powers; for then the diamond and sapphire lenses may be made so much thinner, as greatly to reduce the aberration.

* The figure of the lens is supposed to be plano-convex, the convex side being turned towards parallel rays.

But although eye pieces, on account of their small size, may sometimes be made of the precious gems, yet this can rarely be the case on account of the great expense attending them. It is obvious also that they cannot be employed for the object lenses. The most successful method of diminishing spherical aberration in eye pieces of glass, is by a combination of plano-convex lenses, by means of which a given refracting power may be attained with far greater distinctness than by a single lens of the same power. Thus, when two plano-convex lenses are placed as in Fig. 307, it is found that the image has four times the distinctness of a double convex lens of equivalent power.* Here F is a lens which would bring the parallel rays to a focus and form the image at the distance of G; but E is another similar lens, which, receiving them in a converging state, makes them converge more and come to a focus at H. The double convex lens D, would do the same, but with much greater spherical aberration. It appears, indeed, that the spherical aberration may be wholly removed by combining a meniscus with a double convex lens of certain curvatures.†

Fig. 307.



998. In object glasses, which, on account of their smaller curvatures, are not so subject to error from spherical aberration as eye-glasses are, the most advantageous form is that of a double convex lens of unequal curvatures, the radii of the opposite surfaces being as one to six, (Art. 898.) and the flat side being turned towards the parallel rays.

In short it appears, that in order to avoid the errors arising from spherical abberration, in large lenses, they must be made as thin as convenience will permit; that where it is practicable, they may be most advantageously formed of the precious gems, particularly the diamond; that a plano-convex lens with its convex side towards the parallel rays has less aberration than a double convex lens of equiv-

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* The Scioptic Ball, used in the camera obscura, (Art. 956.) is formed of two such lenses.

† See Brewster's Optics, p. 58, or Herschel on Light, Sec. 316.

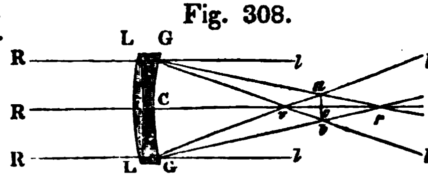
alent power; that two plano-convex lenses may be so combined as to have only ¼ as much aberration as the double lens, and a meniscus may be so united to a double convex lens as wholly to prevent aberration; and finally, that the aberration may be reduced to a very small error simply by employing a double convex lens whose curvatures on the opposite sides are as 1 to 6.

Since lenses having the curvature of one of the conic sections are free from spherical aberration, Sir Isaac Newton ground an object-glass into the figure of a paraboloid. This was free from the error in question, but involved another still more formidable, since it decomposed the light and gave an image tinged with the colors of the rainbow. On observing this, Sir Isaac pronounced the farther improvement of the *refracting* telescope to be hopeless, and betook himself to exclusive efforts for improving the *reflecting* Telescope. But the combined ingenuity of philosophers and artists, has nearly overcome this error also.

999. The next difficulty therefore to be considered is that which arises from the separation of the prismatic colors, in consequence of the different refrangibility of the different rays, an error which is called *Chromatic Aberration.*

The general principles of Chromatic Aberration, will be readily comprehended by calling to mind, that distinct images are formed only when the rays of the same pencil which flow from any point in the object are collected into one and the same point in the image, unmixed with rays from any other point; that the prismatic rays which compose white light have severally different degrees of refrangibility, some being more turned out of their course than others, in passing through the same medium; that, consequently, the different colored rays of the same pencil would meet in different points, each set of colored rays forming its own image, but all these images becoming blended with one another, and thus composing a confused, colored picture.

Fig. 308.



To illustrate these principles let LL be a lens of crown glass, and RL, RL, rays of white light incident upon it, parallel to its axis R*r*. Let the extreme *vio-*

let rays whose index of refraction is 1.54666, be refracted so as to meet the axis in *v*; then the extreme *red*, whose index of refraction is only 1.5258, will meet the axis at some point more distant from the lens as at *r*. C*v* and C*r* are the focal distances of the lens for the violet and the red rays respectively. The distance *vr* is the chromatic aberration, and the circle whose diameter is *ab*, which passes through the focus of the mean refrangible rays at *o*, is called the *circle of least aberration*.

1000. These effects may be shown experimentally by exposing the lens LL, (Fig. 308.) to the parallel rays of the sun. If we receive the image of the sun on a piece of paper placed between *o* and C, the luminous circle on the paper will have a *red* border, because it is a section of the cone L*a* *b*L, the exterior rays of which L*a*, L*b*, are red; but if the paper is placed at any greater distance than *o*, the luminous circle on the paper will have a *violet* border, because it is a section of the cone *l'abl'*, the exterior rays of which *al'*, *bl'* are violet, being a continuation of the violet rays L*v*, L*v*. As the spherical aberration of the lens is here combined with its chromatic aberration, the undisguised effect of the latter will be better seen by taking a large convex lens LL, and covering up all the central part, leaving only a small rim round its circumference at LL, through which the rays of light may pass. The refraction of the differently colored rays will then be finely displayed by viewing the image of the sun on the different sides of *ab*.

It is clear from these observations, that the lens will form a violet image of the sun at *v*, a red image at *r*, and images of the other colors of the spectrum at intermediate points between *r* and *v*; so that if we place the eye behind these images, we shall see a confused image possessing none of that sharpness and distinctness which it would have had if formed only by one kind of rays.*

The separation of white light into its prismatic colors, is called *Dispersion*; and the comparative power of effecting this separation, possessed by different media, is called the *Dispersive power*. The dispersive power is measured by the ratio which, in any case, the separation of the red and violet rays bears to the mean refraction

* Brewster's Optics, p. 79.

of the compound ray. Thus if a ray of solar light on passing through a lens, is turned out of its original direction 27°, and the red and violet rays are separated from each other 1°, then the dispersive power is said to be $\frac{1}{27}$, which is usually expressed in the form of a decimal fraction, $.037=\frac{1}{27}$.

1001. *Different bodies possess different dispersive powers.*

The dispersive powers of a few of the most important substances in relation to the subject before us, are exhibited in the following table.

	Dispersive Power.		Dis. Power.
Oil of Cassia,	0.139	Plate Glass,	0.032
Sulphuret of Carbon,	0.130	Sulphuric Acid,	0.031
Oil of Bitter Almonds,	0.079	Alcohol,	0.029
Flint Glass,	0.052	Rock Crystal,	0.026
Muriatic Acid,	0.043	Blue Sapphire,	0.026
Diamond,	0.038	Fluor Spar,	0.022
Crown Glass, (green,)	0.036		

From this table it appears, that the transparent substances which have the highest dispersive power, are the oil of cassia and the sulphuret of carbon, both of which fluids have been made to perform an important service in the construction of achromatic telescopes; that flint glass, as that used for decanters, has a much higher dispersive power than crown glass, or that which is analogous to window glass; that the diamond has a low dispersive power, but is exceeded in this respect by rock crystal, the sapphire, and fluor spar, which last bodies have the least dispersive power of any known substances.

1002. With these facts in view, we may now inquire *by what means the object glass of the Telescope is rendered achromatic.*

If we place behind LL (Fig. 308.) a concave lens GG of the same glass, and having its surfaces ground to the same curvature, such a lens having properties directly opposite to those of the convex lens will neutralize its effects. Consequently, the rays which were separated into their prismatic colors by the convex lens will be reunited by the concave lens, and reproduce white light. But though such a combination of the two lenses will correct the color, yet it also

destroys the power of the convex lens to form an image, on which its use solely depends. Could we find a concave lens which would correct all the color and yet not destroy this refracting power, the two lenses would evidently form the achromatic combination sought for. Now this is what is actually done: by making the concave lens of a substance which has a *higher dispersive power* than that of which the convex lens is made, the curvature of the concave lens will not need to be so great as that of the convex lens, and of course the two together, constituting the compound lens, will be equivalent in refracting power to a single lens, whose convexity is equal to the difference of their curvatures. The most common combination is that of flint glass with crown glass, the concave lens being made of flint glass, and the convex of crown. By the table in Art. 1001, it will be seen that the dispersive power of flint glass is 52 while that of crown glass is 36, which numbers are nearly as 3 to 2, and these numbers, therefore, may be employed for the sake of illustration. Since the power of the concave lens to reunite the prismatic rays is so much greater than that of the convex lens to separate them, we shall not require a refractive power to effect this equivalent to that of the convex lens; that is, a concave lens of less curvature and proportionally greater focal distance, will serve our purpose. Therefore,

An achromatic lens is formed by the union of a convex and a concave lens, whose dispersive powers are respectively proportional to their focal distances.

1003. A telescope furnished with an object glass thus formed, is called an *Achromatic Telescope*. The spherical aberration being corrected by the methods pointed out in Art. 996, and the chromatic aberration being destroyed in the manner above described, the Refracting Telescope becomes an instrument of great perfection, and is reckoned among the greatest works of art. Until recently, it was rare to meet with Refracting Telescopes of an aperture of more than from three to five inches. For we have already seen that the errors of spherical and chromatic aberration increase rapidly as the size of the aperture is augmented.

1004. If it be asked, what is the *use* of a large aperture, since the magnifying power does not depend upon the diameter of the

object glass, but upon the ratio between the focal distance of the object glass and the focal distance of the eye glass, (Art. 993.) we answer, that the use of a large aperture is to admit, condense, and finally convey to the eye, a larger beam of light, and thus to render many objects, as the smaller stars, or Jupiter's belts, visible, which otherwise would not be so, on account of the feebleness of the light which they transmit to us. *Want of light* is in fact one of the greatest difficulties that the telescope has to contend with; for, in the first place, the object glasses of most telescopes are comparatively small, and are necessarily so on account of the difficulty of procuring suitable glass for those of a larger size; and in the second place, of the light admitted through the object glass, a great proportion is intercepted and wasted in various ways, many instruments being able to save only the central rays without rendering the image indistinct and colored. Thus, when very high magnifiers are applied, (which of course have very small focal distances,) the rays proceed from the focus and fall upon the microscope so obliquely, that only those which pass through the central parts of the lens can be saved, since such as fall upon the marginal parts of the lens are too much affected by spherical and chromatic aberration, to form with the others a distinct and colorless image.

1005. *Want of field of view* is another difficulty to be surmounted. When we use an object glass of short focus with a high magnifier, the microscope must have a focus proportionally short, and of course the field of view will be very limited and the light but feeble. This difficulty may be obviated by using an object glass of very great focal distance. If, for example, the focal distance of the object glass were only 12 inches, in order to attain a magnifying power of 120, we must employ a microscope whose focal distance is only $\frac{1}{10}$th of an inch. But if the focal distance of the object glass were 10 feet, or 120 inches, then our microscope might have a focal distance of 1 inch, which would give a larger field and a stronger light. With the view of obviating several of the foregoing difficulties, the earlier astronomers who used the telescope employed for their object glasses lenses whose focal lengths were very great. Cassini, an Italian astronomer, constructed telescopes eighty, one hundred, and one hundred and thirty six feet long; and Huygens employed such as were

nearly the same length. The latter astronomer dispensed with the tube, fixing his object glass, contained in a short tube, to the top of a high pole, and forming the image in the air near the level of the eye, which image he viewed with an eye glass, as usual. With telescopes of this description, several of the satellites of Saturn were discovered.

1006. But one of the most formidable difficulties hitherto encountered in the construction of large Refracting Telescopes, has arisen from the *imperfections of glass*. When Dollond (the English artist who first perfected the Achromatic Telescope,) engaged in the manufacture of his instruments, he fortunately had possession of a considerable quantity of very fine glass; but when that was used up, no more of equal quality could be obtained in England.* On the continent, however, one or two celebrated artists have been more successful. The most distinguished manufacturer of optical glass was M. Guinand of Switzerland, who died in 1823, who greatly excelled all his predecessors or cotemporaries in fabricating large masses of perfectly homogeneous glass. But even he could produce disks of twelve or eighteen inches in diameter in no other way, than by selecting the purest specimens of smaller pieces, and joining them together. In 1805, M. Fraunhofer of Bavaria, a celebrated manufacturer of telescopes, invited Guinand to become his associate in the manufacture of optical glass; and from the united efforts of these most ingenious men, proceeded glass of unexampled transparency and purity. Fraunhofer has recently deceased, and the *difficulty* of procuring perfect glass is renewed. This induced the Royal Society of London to appoint a committee to institute new experiments on this subject. These have been prosecuted with the greatest ability, but have as yet produced no important results.

The difficulty of obtaining glass of a perfectly homogeneous composition and structure is thus set forth by Mr. Faraday, who con-

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* The present Mr. Dollond, a successor of the inventor of Achromatic Telescopes, "has not been able to obtain a disk of flint glass four inches and a half in diameter, fit for a telescope, within the last five years, or a similar disk of five inches diameter within the last ten years."—*Faraday*, Phil. Trans. 1830.

ducted the chemical part of the above experiments. "Although every part of the glass may in itself be as good as possible, yet without this condition [a perfectly homogeneous structure] the parts do not act in uniformity with each other; the rays of light are deflected from the course which they ought to pursue, and the piece of glass becomes useless. The streaks, striæ, veins or tails, which are seen within glass otherwise perfectly good, result from a want of this equality; they are visible only because they bend the rays of light which pass through them from their rectilinear course, and are constituted of a glass having either a greater or a smaller refractive power than the neighboring parts. When these irregularities are so powerful as to render their effects observable by the naked eye, it may easily be supposed to what an injurious extent their influence must extend in the construction of telescopes and other instruments of a similar nature, where these faults are not only magnified many times, but where the effect is to give an equally magnified erroneous representation of the object looked at, when the very point to be attained is to examine that object with the utmost accuracy; and it is accordingly found that these striæ are the most fatal faults of glass intended for optical purposes. Besides this, not only do the striæ themselves occasion harm, but there is every reason to believe that they rarely occur in glass otherwise homogeneous. Sometimes, it is true, a grain of sand, in passing through, and at the same time dissolving in glass, will give a streak of different composition to the rest of the substance; and at others, a bubble ascending may lift a line of heavy or more refractive matter into a lighter and less refractive portion above. Many a disk, which upon the most careful examination has appeared perfectly free from striæ, and quite uniform, has, when worked into an object glass, been found incapable of giving a good image, on account of the existence of irregularities in the mass, which, though not sudden or strong enough to occasion striæ, still produce a confused effect; and if this happens with glass approaching so near to perfection, it happens still more frequently, and to a much stronger degree, with such as contain visible irregularities."*

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* *Faraday*, Phil. Tr. 1830.

1007. These irregularities are much more frequent in flint glass than it crown; and by far the greatest obstacle to be overcome in constructing a large refracting telescope, is to procure a suitable piece of flint glass for the concave part of the achromatic object glass. (Art. 1002.) This want of uniformity arises, chiefly, from the *different specific gravities* of the materials that compose the glass. Oxide of lead, a very heavy substance, enters into the composition of flint glass to the amount of about one third of its weight. The oxide of lead is so heavy a material, and at the same time so fusible, that it melts and sinks to the bottom, leaving the lighter materials to accumulate at the top: and so imperfect are the means of mixture, under ordinary circumstances, that glass of very different specific gravity, is procured from the bottom and the top of the same crucible.

1008. These circumstances we have thought worthy of being recited in order to impress on the mind of the learner the formidable nature, as well as the great number, of the difficulties to be overcome in the construction of a large Achromatic Telescope. Yet they have, in several instances, been completely surmounted. Fraunhofer executed two telescopes with achromatic object glasses, the one nine inches and nine tenths, and the other twelve inches in diameter; and at the period of his death he was proposing to undertake one eighteen inches in diameter. That of 9.9 inches aperture was made for the Russian government for the use of the observatory at Dorpat, where under the direction of M. Struve, a distinguished astronomer, it has already achieved several valuable discoveries in astronomy. The object glass has a focal length of twenty five feet. The concave part of the compound lens is formed of a dense flint glass made by Guinand, and has a greater dispersive power than any obtained before. It is perfectly free from veins, and nearly free from every impurity. The instrument has four eye glasses varying in magnifying power from one hundred and seventy five to seven hundred.*

* It is said that, as a general rule, Achromatic Telescopes are priced in the ratio of the *cube* of the aperture. If a telescope with an object glass three inches in diameter, is valued at five hundred dollars, one of twelve inches would cost sixty four times as much, that is, thirty two thousand dollars.

1009. The great difficulty of procuring perfect glass for achromatic telescopes, has lead opticians to attempt the construction of lenses for this purpose out of some transparent fluid which might be inclosed in thin glass. Such a medium seemed pecularly suited to take the place of the concave lens, in which the principal difficulty resides. Professor Barlow, of the Military Academy of Woolwich, has recently made several telescopes on this principle, the last of which had an aperture of 7.8 inches, and performed as well as the larger kind of achromatic telescopes constructed in the usual way. The fluid employed for this purpose was the sulphuret of carbon, a limpid fluid prepared from sulphur and charcoal.* It is singularly adapted to optical purposes, having a refractive power about equal to that of the best flint glass, with a dispersive power more than double that of the same substance. It is, moreover, perfectly colorless, beautifully transparent, and, although it is very volatile, yet when closely sealed it possesses nearly the same optical properties under all required temperatures. The advantages of using sulphuret of carbon, should the experiments finally succeed as well as is expected, are the following:

1. It renders us independent of flint glass.

2. It enables us to increase the aperture of the telescope to a very considerable extent.

3. It gives us all the light, field, and focal power of a telescope of one and a half times at least, probably twice the length of the tube.†

4. The expense of large telescopes (which consists mainly in the cost of the object glass) is greatly diminished, the most expensive part being supplied with less than one ounce of sulphuret of carbon of the value of three shillings.‡

The Terrestrial or Day Telescope.

1010. As the Astronomical Telescope represents objects inverted, it requires to be so modified for terrestrial views, that objects may appear erect. This is effected by the addition of two more lenses of similar figure to that of the eye glass, and of the same focal length. The first of these additional glasses forms a second image of the

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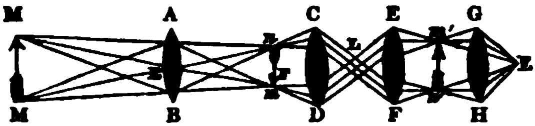
* Silliman's Chemistry, Vol. I, p. 363.

† *Barlow*, Phil. Tr. 1828. ‡ Ib. Phil. Tr. 1829.

object inverted with respect to the first image and therefore erect with respect to the object. This image is viewed by the second glass as by any simple microscope. Thus, AB, the object glass

Fig. 309.



forms an inverted image *nm* of the object MN. Instead of viewing this image by the eye placed at L, as in the common astronomical telescope, we suffer the pencil of parallel rays to cross each other at L and fall upon a second lens EF (similar in all respects to CD) which collects them into an image *m′n′* in its focus of parallel rays, which image is viewed by the eye-glass GH in the same manner as the object itself would be.

As some portion of the light is reflected, and some absorbed and dissipated by passing through these additional lenses, they of course diminish the brightness of the view; but in the day time there will usually be light enough for distinct vision after this loss is sustained, while it is more agreeable and convenient to have the objects presented to us in their natural positions than inverted. It will be remarked that the additional lenses do not magnify, the focal length of each being the same as that of the first eye-glass. Were they rendered smaller for the purpose of magnifying, the field of view and the light would both be impaired.

1011. We usually find in telescopes, particularly those designed for terrestrial objects, some contrivance, as a draw-tube, by which the eye-glass can be brought nearer to, or withdrawn from the object-glass. This is to accommodate the instrument to objects at different distances. When it is directed to very near objects, the image is thrown farther back, and therefore in order that it may be in the focus of the eye-glass, (which is essential to distinct vision) the latter must be drawn backward; but where the object is remote, the image is formed nearer to the object glass, and then the eye-glass must be moved forward, till its focus of parallel rays, comes to the place of the image. For a similar reason, near sighted persons require the eye-glass to be brought nearer than usual to the object-

glass; for then the image will be nearer to the eye-glass than its focus of parallel rays, and the rays will meet the eye diverging, a condition favorable to eyes naturally too convex. For a contrary reason, long-sighted persons, who usually wear convex spectacles, may adjust the telescope to suit their eyes without spectacles, by removing the eye-glass farther back than usual.

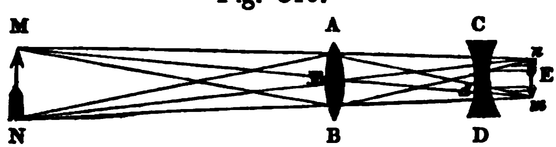
Most terrestrial telescopes contain a greater number of glasses than are represented in figure 309. Such a number are used for the purpose of correcting spherical and chromatic aberration, these errors being less in several flat and thin lenses than in a smaller number of equivalent lenses of greater curvature.

Astronomical telescopes are easily adapted to terrestrial observations, by removing the eye-glass and substituting a tube containing the additional glasses for rendering the view erect.

Galileo's Telescope.

1012. This instrument was the first astronomical telescope, having been invented by Galileo, as the name implies. It differs from the common astronomical telescope, in having for the eye-glass a *concave* instead of a convex lens, which receives the pencils of light, as they are converging to form an image, at such a distance from the focus to which tend, as to render them parallel. Thus the object-

Fig. 310.



glass AB collects the rays of light as they proceed from the object MN, and makes them converge towards the focus at E. But the concave lens CD is interposed at such a point as to render these converging rays parallel, and in this way they come to the eye situated behind the lens.

Since the concave lens restores the rays to that state of parallelism which they had before they passed through the object-glass, the learner may not readily see how this instrument aids the eye. That

it does so, however, will be apparent from the following considerations.

First, a much broader beam of light falls upon the object-glass than the naked pupil of the eye, the greater part of which is collected and conveyed to the eye. By this means the *brightness* of objects is greatly increased.

Secondly, as in the astronomical telescope, (Art. 993,) were the eye situated at the center of the object, the object and the image formed by the object-glass would have the same apparent dimensions; and inasmuch as the eye-glass enables us to view this image much nearer, it increases its apparent dimensions in the same ratio. But when we use a concave lens situated as in the Galilean telescope, the effect is the same as that of a convex lens situated in the same manner on the other side of the focus, so that the rays, would come to the eye parallel. Hence, in the Galilean as in the common astronomical telescope, the magnifying power is as the ratio of the focal distance of the object-glass to that of the eye-glass.

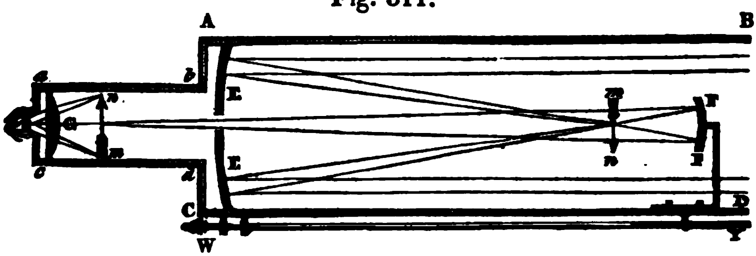
This form of the telescope has several advantages and several disadvantages when compared with the ordinary form. In the first place, requiring but two glasses to present objects erect, it occasions less loss of light than the ordinary form, and presents objects with proportionally greater brightness. In the second place, the eye-glass being *between* the object-glass and the image, instead of *beyond* it, the instrument admits of being made short and compact, a circumstance which fits it for the purposes of an *opera-glass*, to which use it is frequently applied. In the third place, the concave lens corrects the chromatic aberration of the convex lens and where a proper proportion is observed between the curvatures of the two lenses, the instrument is easily rendered achromatic. The chief disadvantage attending the instrument, is its limited *field of view*. For the pencils of parallel rays, after passing through the concave eye-glass, diverge from one another, those towards the marginal parts of the lens being turned from those that are contiguous to the axis, and therefore not entering the pupil of the eye. And since only those near the axis at E (Fig. 310.) can enter the pupil, the field of view must depend on the dimensions of the pupil, and cannot be increased by increasing the length of the instrument, as in the refracting telescope. This defect has caused this kind of telescope to fall into disuse for astronomical purposes.

Reflecting Telescopes.

1013. Reflecting Telescopes differ in principle from those already described only in forming their image by a *concave reflector*, instead of a convex object-glass. The most common form of the Reflecting Telescope, is the *Gregorian*, so called from the inventor, Dr. James Gregory, of Scotland. The general principles of this instrument may be explained as follows:

In the Gregorian Telescope, the light (supposed to come in parallel rays) is first received by a large concave speculum, by which it is brought to a focus and made to form an inverted image. On the opposite side of this image, and facing the large speculum, is placed a small concave speculum, of greater curvature, at such a distance from the image that the rays proceeding from it and falling on the speculum are made to converge to a focus situated a small distance behind the large speculum, passing through a circular aperture in the center of it. This second image is magnified by a microscope as in the Refracting Telescope. This description may now be applied to the annexed figure.

Fig. 311.



ABCD, a large open tube of brass, iron, or mahogany to contain the reflectors.

abcd, a smaller tube to receive the second image and the eye glass.

EE, large concave speculum, usually composed of a metallic compound called *speculum metal*.

FF, small concave speculum.

mn, image formed by the large reflector.

nm, image formed by the small reflector.

G, eye glass.

WY, a metallic rod having a screw connected with the small reflector, by means of which this reflector is made to approach the first image or to recede from it.

Some of the pencils of rays necessary to form the respective images are omitted in the figure to prevent confusion.

1014. From the foregoing construction it is evident, first, that the image viewed by the eye being in the same position with the object, the latter will appear *erect*; secondly, that since the mirrors may be formed of a parabolic figure,* all *spherical aberration* may be easily prevented (Art. 861.); thirdly, that since light is not decomposed by reflexion, reflecting telescopes are not subject to *chromatic aberration*; and, hence, that it is not necessary to lengthen the tube as the aperture is increased, as is the case in refracting telescopes (Art. 1005.); but since the light will depend, chiefly, on the size of the large reflector, a strong light may be obtained with a comparatively short tube. The achromatic telescope, however, with all the latest improvements, is deemed a more perfect and more convenient instrument than the reflecting telescope; and it is supposed that there will be no occasion hereafter to construct reflectors of such enormous dimensions as those of Dr. Herschel. Some account of his forty feet reflector may form a suitable close to this sketch of optical instruments.

1015. Under the munificent patronage of George III, Sir William Herschel began, in 1785, to construct a telescope forty feet long, and in 1789, on the day when it was completed, he discovered with it the sixth satellite of Saturn. The great speculum was more than *four feet* in diameter, and weighed two thousand one hundred and eighteen pounds. Its focal length was forty feet. The tube which contained it was made of sheet iron.

The *light* afforded by this instrument was astonishingly great. The largest fixed stars, as Sirius, shone in it with the splendor of the sun. The reason of this will be obvious when we reflect that it collected and conveyed to the eye, in the place of the small beam that enters the naked organ, a beam of light from the star more than four feet in diameter. Hence it was suited to reveal to the eye numberless stars and clusters of stars, which preceding telescopes

* An elliptical figure has the same property.

had failed to exhibit, because they could not collect a sufficient quantity of their light. To economize the light to the best advantage, the small mirror employed in the Gregorian telescope (see Fig. 311.) was dispensed with, since every successive reflexion dissipates a considerable portion of the light, and the image was thrown near to the open mouth of the tube, where it was viewed by the eye-glass directly, the observer being seated so as to look into the mouth in front. In order to prevent the head from obstructing too much of the light, the image was formed near one side of the tube. Its greatest magnifying power was six thousand four hundred and fifty; but this was used only for the smallest stars.

This great telescope was mounted out of doors in a frame of proportional size; but by exposure to the weather, the frame has recently become so much decayed that it has been taken down and another telescope of twenty feet focus erected in its place, with which Sir J. Herschel is prosecuting, with great success, the researches of his father.

APPENDIX.

General Statement of the Undulatory Theory of Light.

[From Herschel's Treatise on Light, *Encyc. Metropolitana*, II. 449.]

The undulatory theory, among whose chief supporters we have to number Huygens, Descartes, Hooke, and Euler, and, in later times, the illustrious names of Young and Fresnel, who have applied it with singular success and ingenuity to the explanation of those classes of phenomena which present the greatest difficulties to the Corpuscular doctrine, requires the admission of the following hypotheses or postulata :

1. That an excessively rare, subtle, and elastic medium or *ether*, as it is called, fills all space, and pervades all material bodies, occupying the intervals between their molecules; and, either by passing freely among them, or, by its extreme rarity, offering no resistance to the motions of the earth, the planets, or comets in their orbits, appreciable by the most delicate astronomical observations; and having inertia but not gravity.

2. That the molecules of the ether are susceptible of being set in motion by the agitation of the particles of ponderable matter, and that when any one is thus set in motion, it communicates a similar motion to those adjacent to it; and thus the motion is propagated farther and farther in all directions, according to the same mechanical laws as those which regulate the propagation of undulation in other elastic media, as air, water, or solids, according to their respective constitutions.

3. That in the interior of refracting media the ether exists in a state of less elasticity, compared with its density, than in vacuo, (i. e. in space empty of all other matter;) and that the more refractive the medium, the less, relatively speaking, is the elasticity of the ether in its interior.

4. That the vibrations communicated to the ether in free space, are propagated through refractive media, by means of the ether in their interior, but with a velocity corresponding to its inferior degree of elasticity.

5. That when regular vibratory motions of a proper kind are propagated through the ether, and, passing through our eyes, reach and agitate the nerves of our retina, they produce in us the sensation of light, in a manner bearing a more or less close analogy to that in which the vibrations of the air affect our auditory nerves with that of sound.

6. That as, in the doctrine of sound, the *frequency* of the aërial pulses, or the number of excursions to and fro from its point of rest, made by each molecule of the air, determines the *pitch*, or note,—so, in the theory of light, *the frequency of the pulses, or number of impulses made on our nerves in a given time, by the etherial molecules next in contact with them, determines the color of the light;* and that, as the absolute extent of the motion to and fro of the particles of air determine the *loudness* of the sound,—so the *amplitude*, or extent of the excursions of the etherial molecules from their points of rest, determine the *brightness* or intensity of the light.

[With these general principles in view, the advocates of the Undulatory Theory proceed to account for all the phenomena of light and colors. The subject is pursued by Sir J. Herschel, in a lucid and able manner, but our limits do not permit us to quote any thing more than the table which, by a remarkable penetration into the arcana of nature, assigns the actual length of an undulation in parts of an inch, corresponding to each color of the spectrum, which the supposed medium undergoes—the number of such undulations that occur in the space of an inch—and the number that happen in one second of time. However incredulous we may be with respect to the possibility of ascertaining facts apparently so far without the pale of human thought, our author (perhaps the most competent judge of our times) avers, "that whatever theory of light we adopt, these periods, and these spaces have a *real existence*, being in fact deduced by Newton from direct measurements, and involving nothing hypothetical but the names here given them."]

Table showing the correspondence of certain undulations to the several colors of the spectrum.

Colors of the spectrum.	Lengths of an undulation in parts of an inch.	Number of undulations in an inch.	Number of undulations in a second.
Extreme red, -	0·0000266	37640	458,000000,000000
Red, - - -	0·0000256	39180	477,000000,000000
Intermediate, -	0·0000246	40720	495,000000,000000
Orange, - -	0·0000240	41610	506,000000,000000
Intermediate, -	0·0000235	42510	517,000000,000000
Yellow, - -	0·0000227	44000	535,000000,000000
Intermediate, -	0·0000219	45600	555,000000,000000
Green, - -	0·0000211	47460	577,000000,000000
Intermediate, -	0·0000203	49320	600,000000,000000
Blue, - -	0·0000196	51110	622,000000,000000
Intermediate, -	0·0000189	52910	644,000000,000000
Indigo, - -	0·0000185	54070	658,000000,000000
Intermediate, -	0·0000181	55240	672,000000,000000
Violet, - -	0·0000174	57490	699,000000,000000
Extreme violet,	0·0000167	59750	727,000000,000000